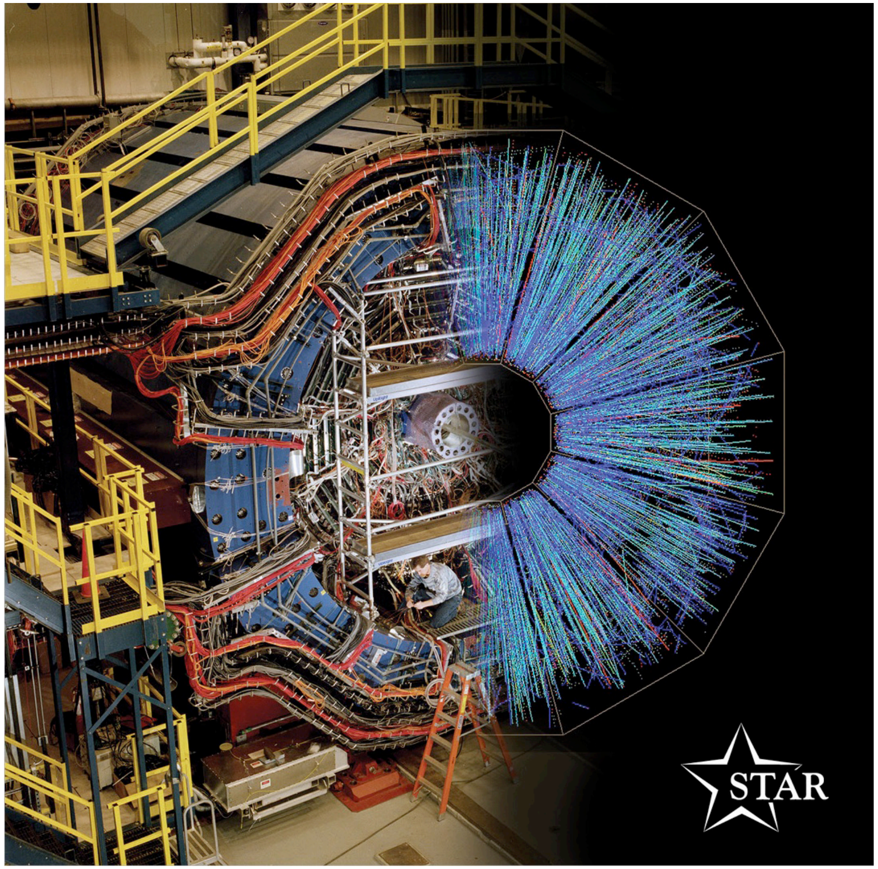
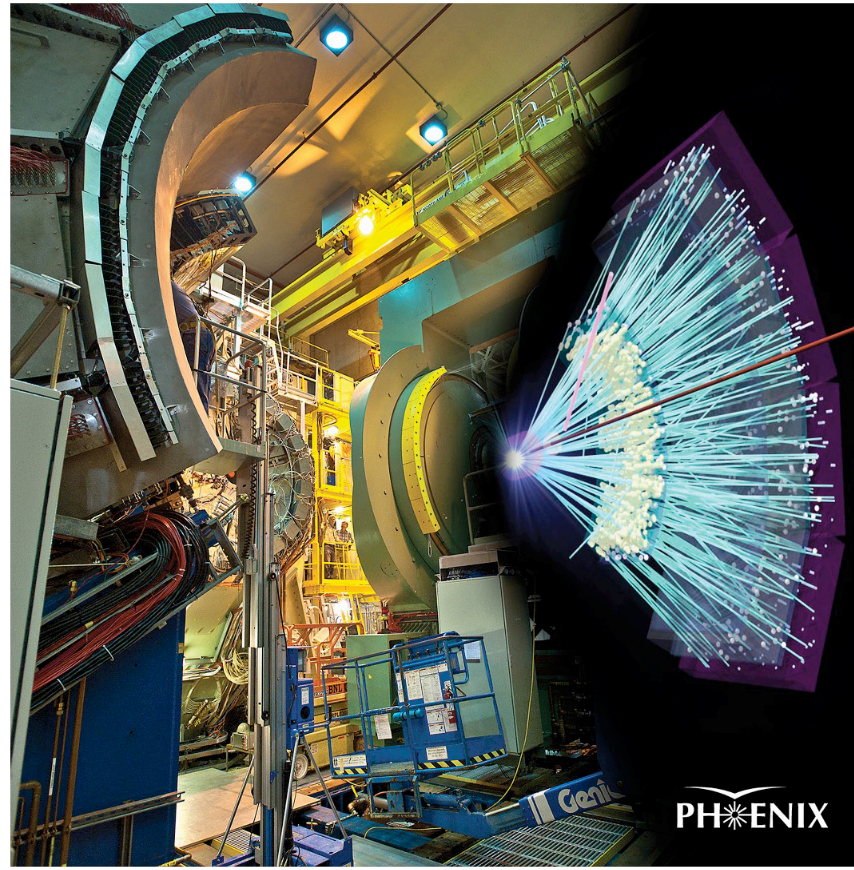
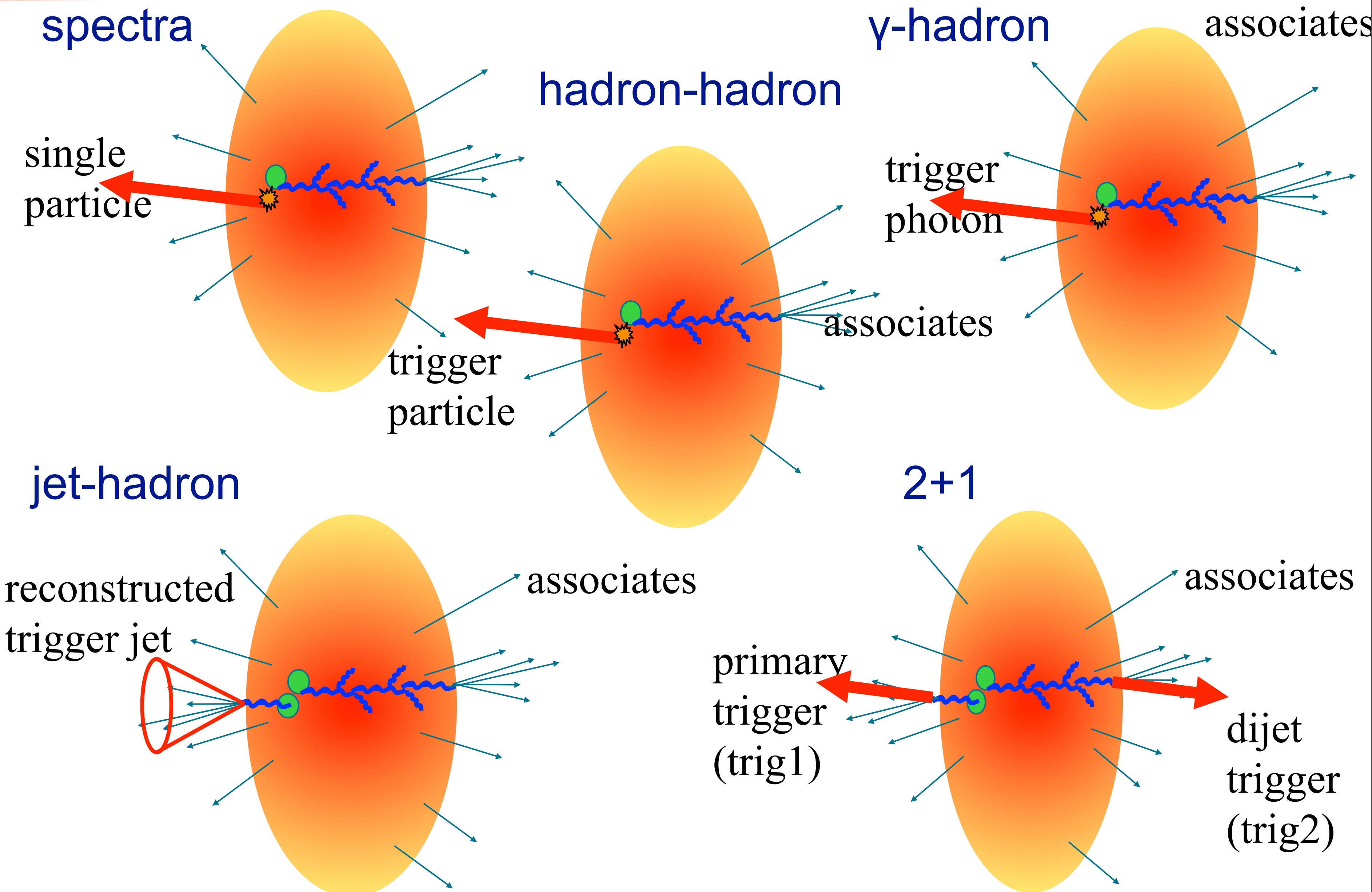
Jet and Jet-like Correlations at RHIC

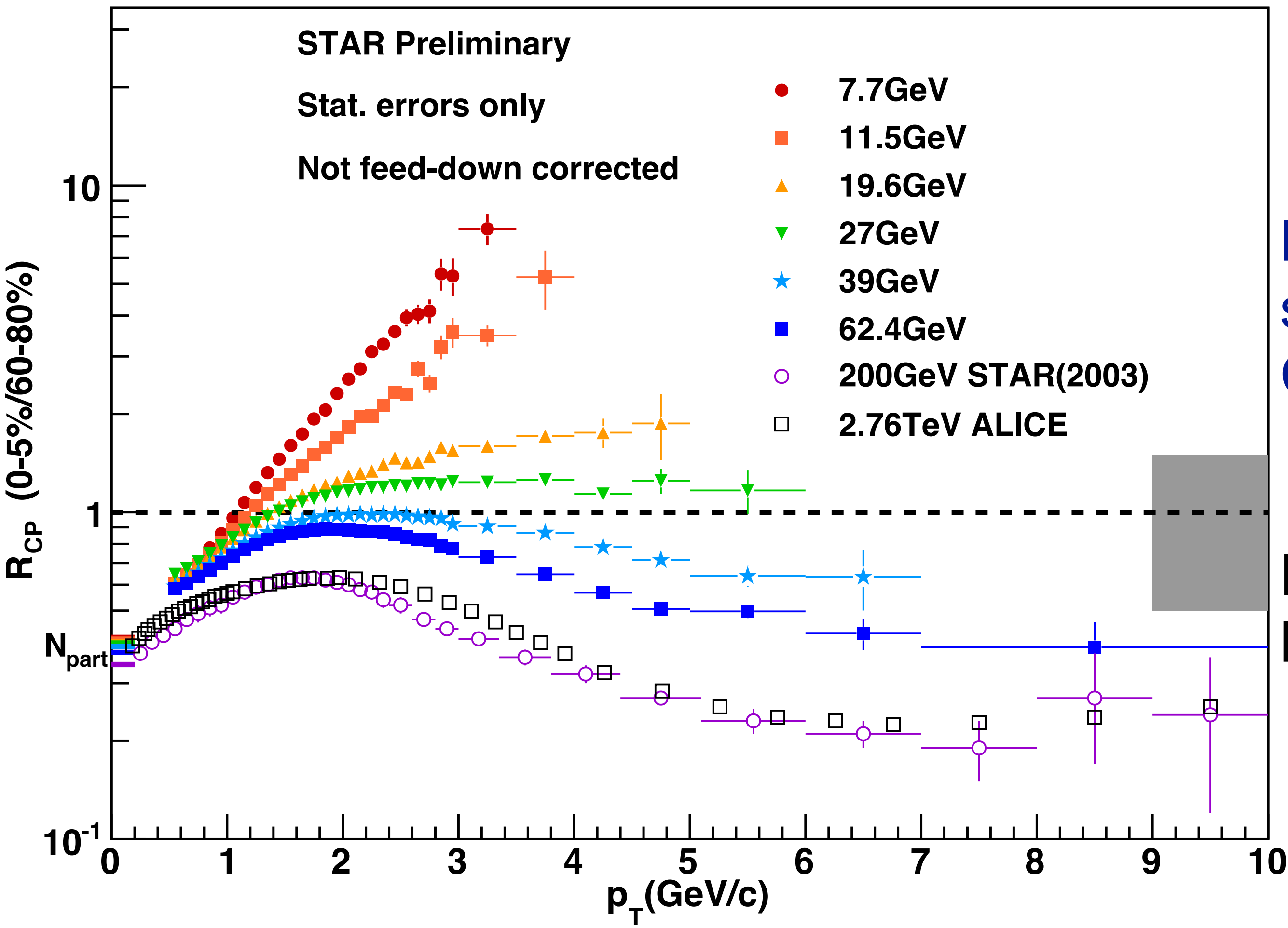




Jet(-like) correlations



Nuclear enhancement at lower energies



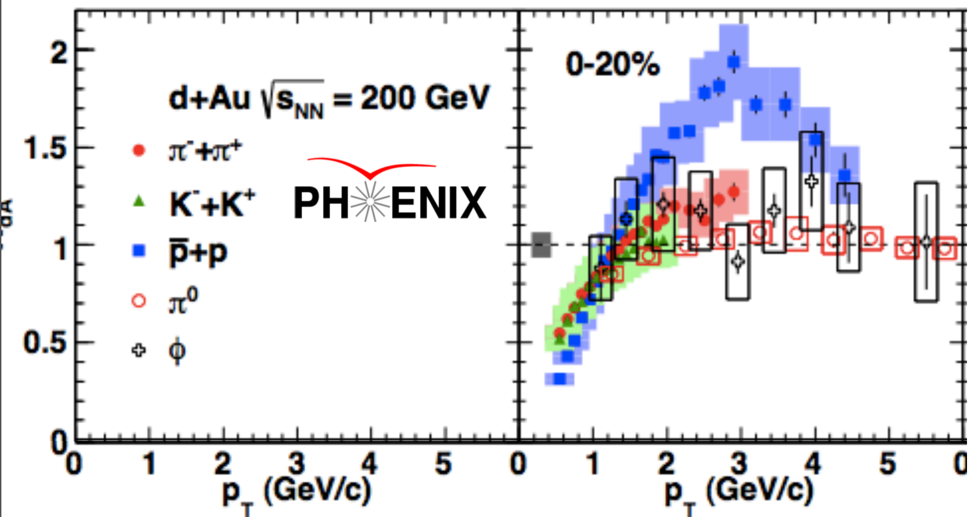
Lower energies strongly enhanced - Cronin effect?

Drops below unity between $\sqrt{s_{NN}}$ = 27- 39 GeV

Note: R_{CP} < 1 does **not** imply the absence of suppression (jet quenching)

Need to disentangle Cronin and parton energy loss effects

Cronin at lower energies

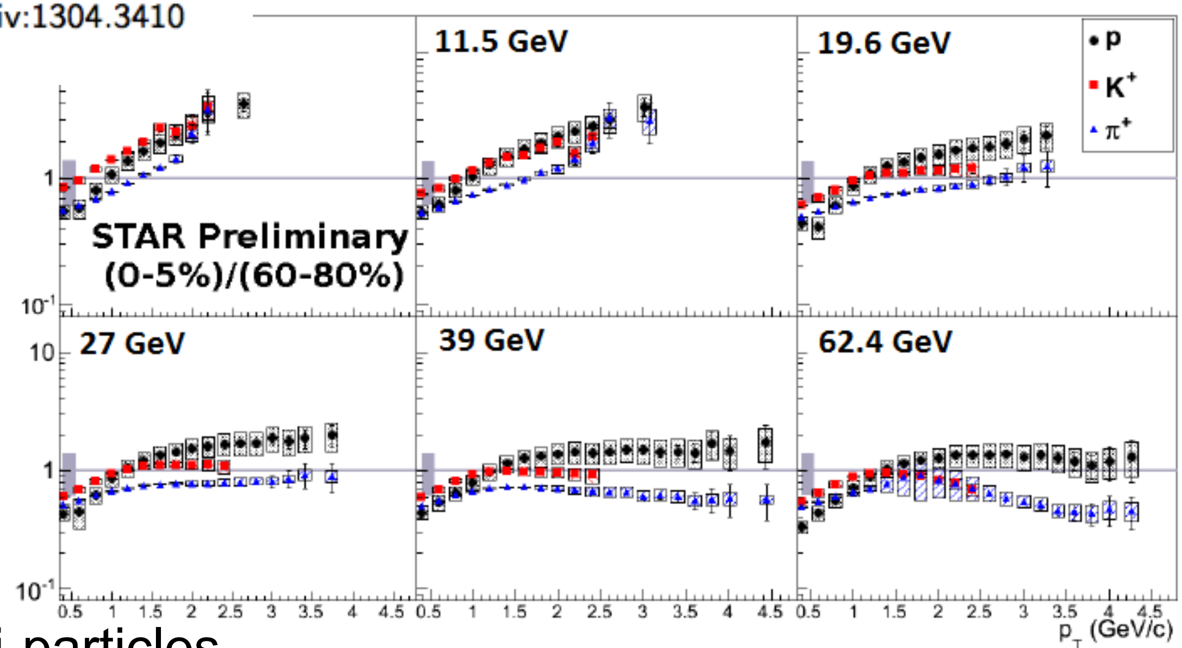


PHENIX, arXiv:1304.3410

Species dependent effect seen as in original Cronin data

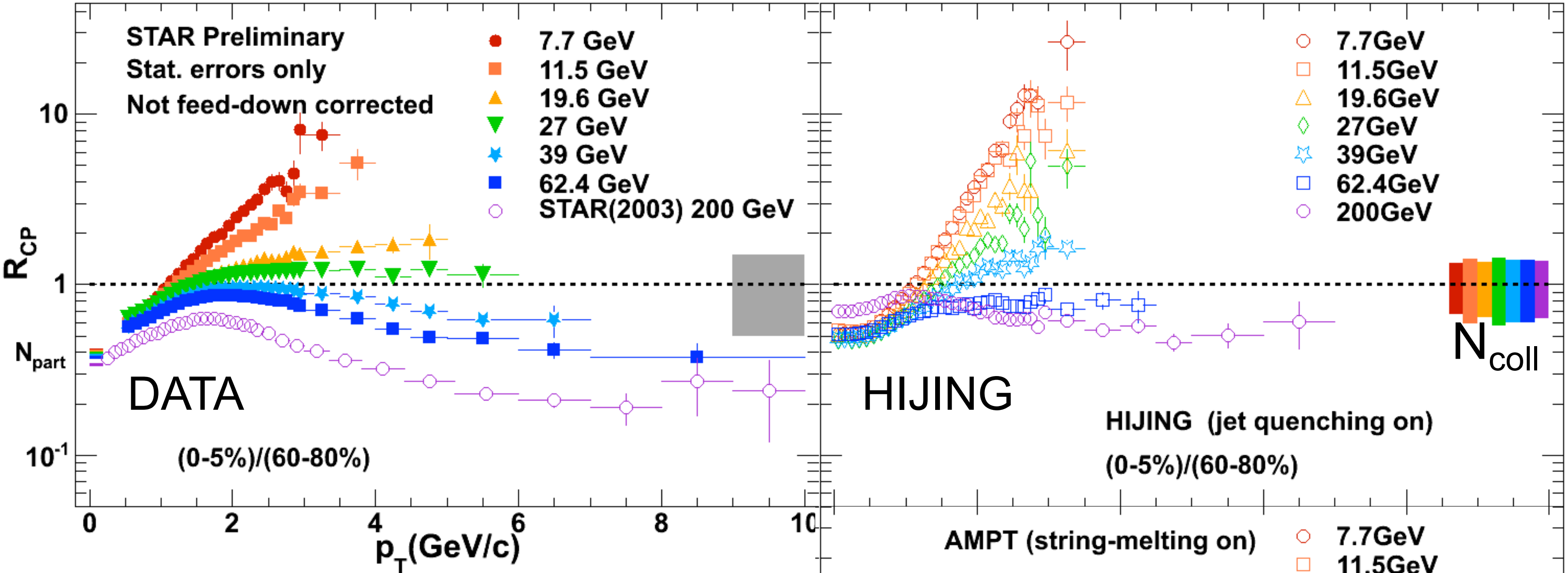
$R_{cp}^{p} > R_{cp}^{K} > R_{cp}^{\pi}$

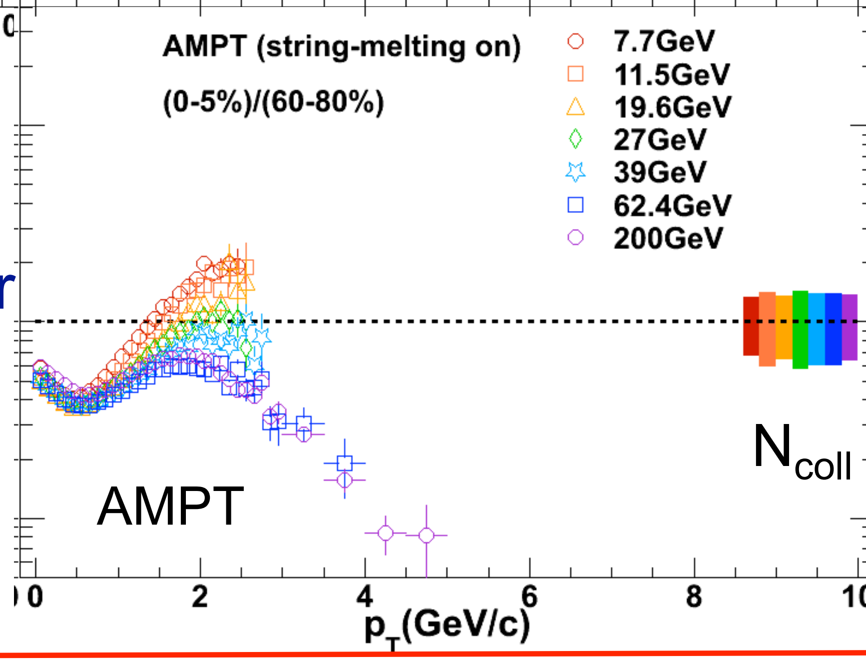
Particle ratios changing as function of $\sqrt{s_{NN}}$



Similar features seen for anti-particles

Comparison to models



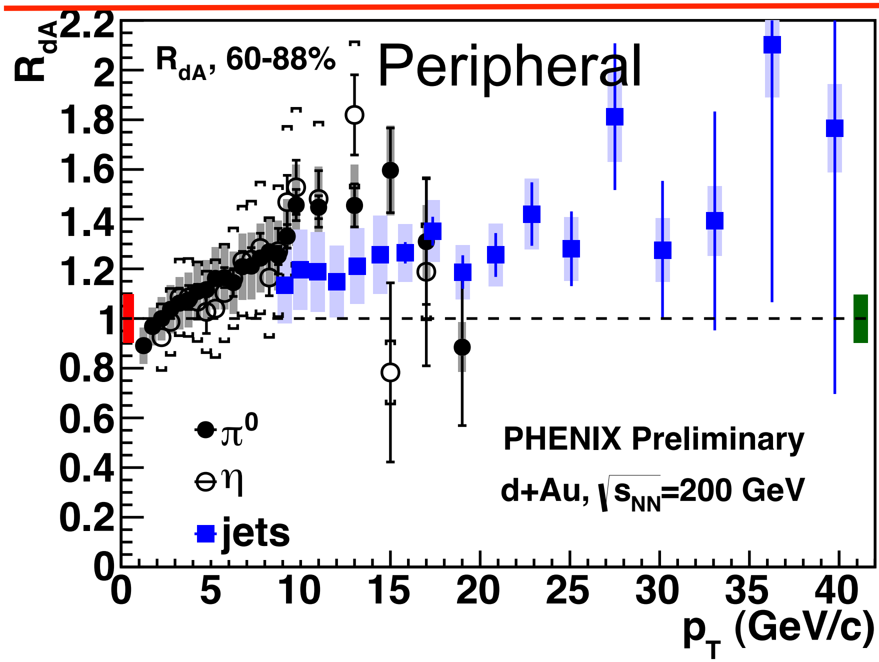


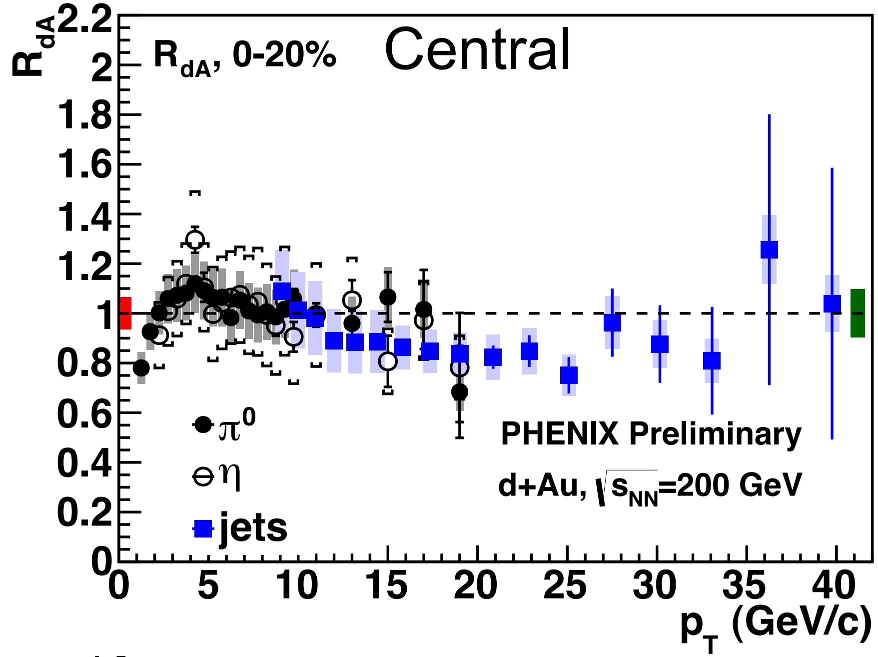
Similar behavior to data

- HIJING
  - 200 GeV - odd low p_T behavior
  - Generally overestimates R_{CP}
- AMPT
  - limited p_T reach

Cronin/flow hard to model

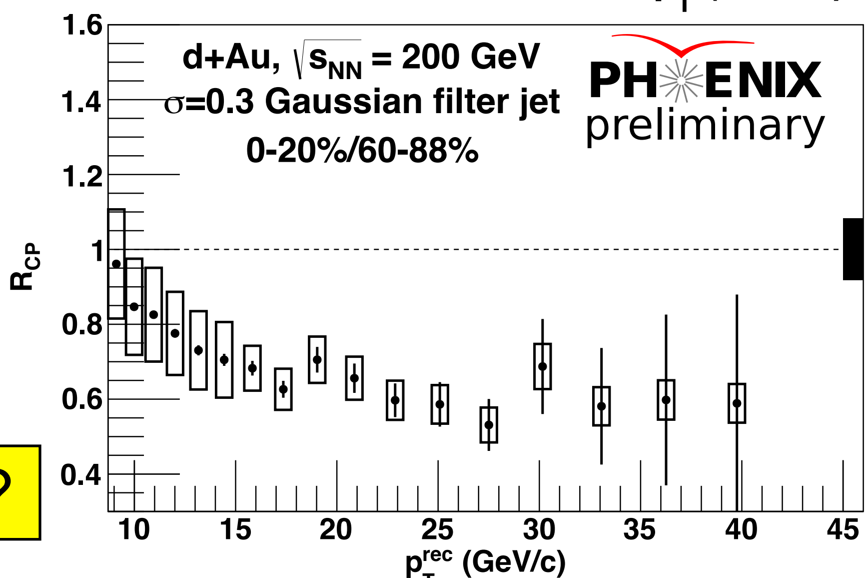
Centrality in d-Au: “loosing control” data





Enhancement larger in peripheral collisions

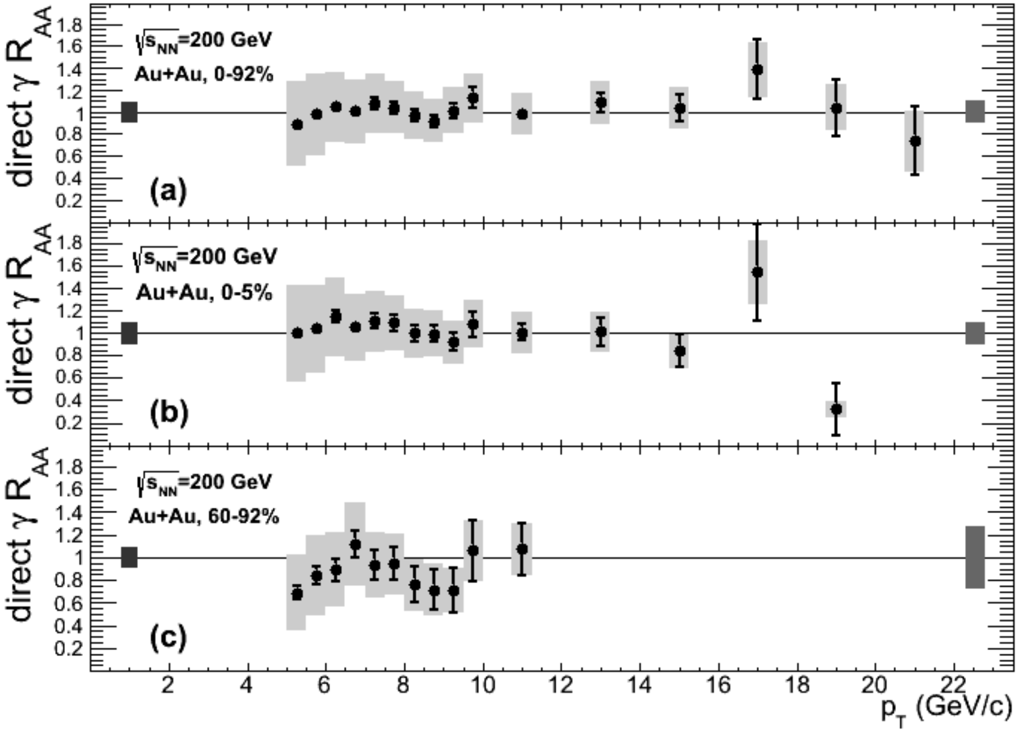
- naive expectation peripheral ~“p-p”



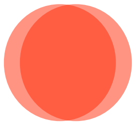
Centrality definition under control?

Photon baseline

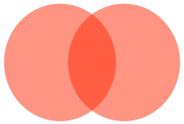
arXiv:1208.1234
I.Vitev et al. PLB669, 337 (2008)



Minimum bias

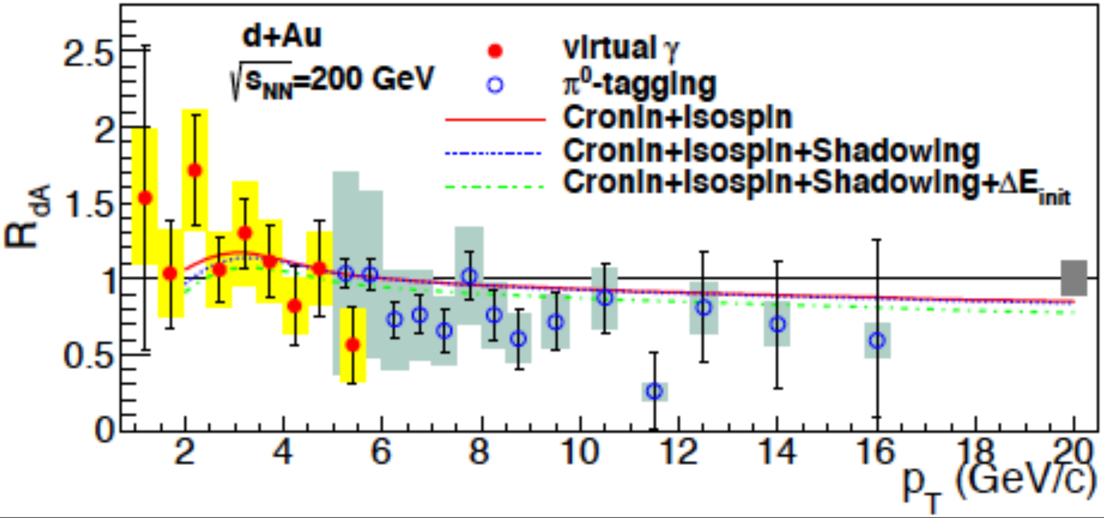


0-5%



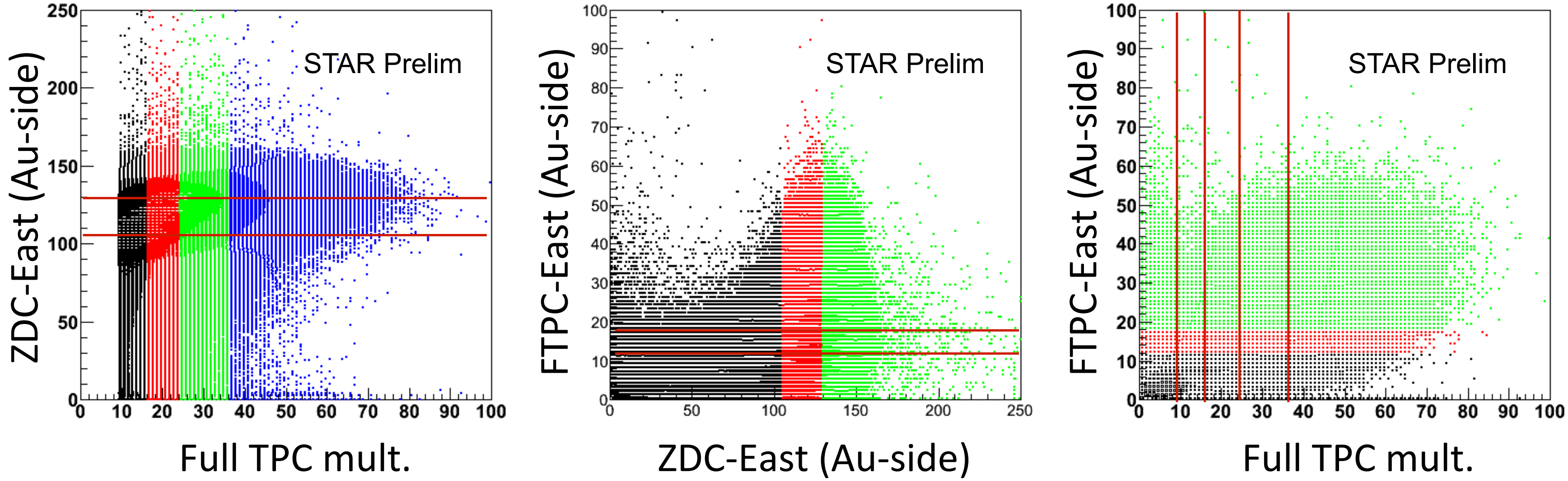
60-92%

R_{dAu} and R_{AA} suggest little to no nuclear effects



Au-Au and Minbias d-Au N_{bin} calculation is correct

Centrality in d-Au

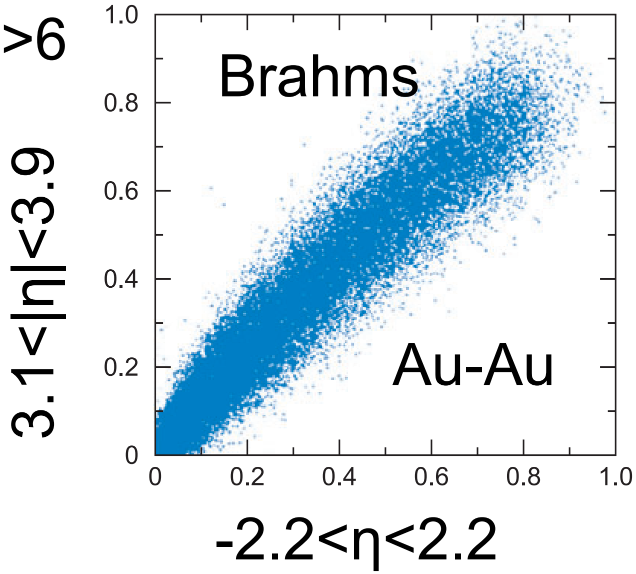


STAR TPC -1<η<1, FTPC 2.8<η<3.7, ZDC η>6

PHENIX 3.1<η<4.9 (BBC)

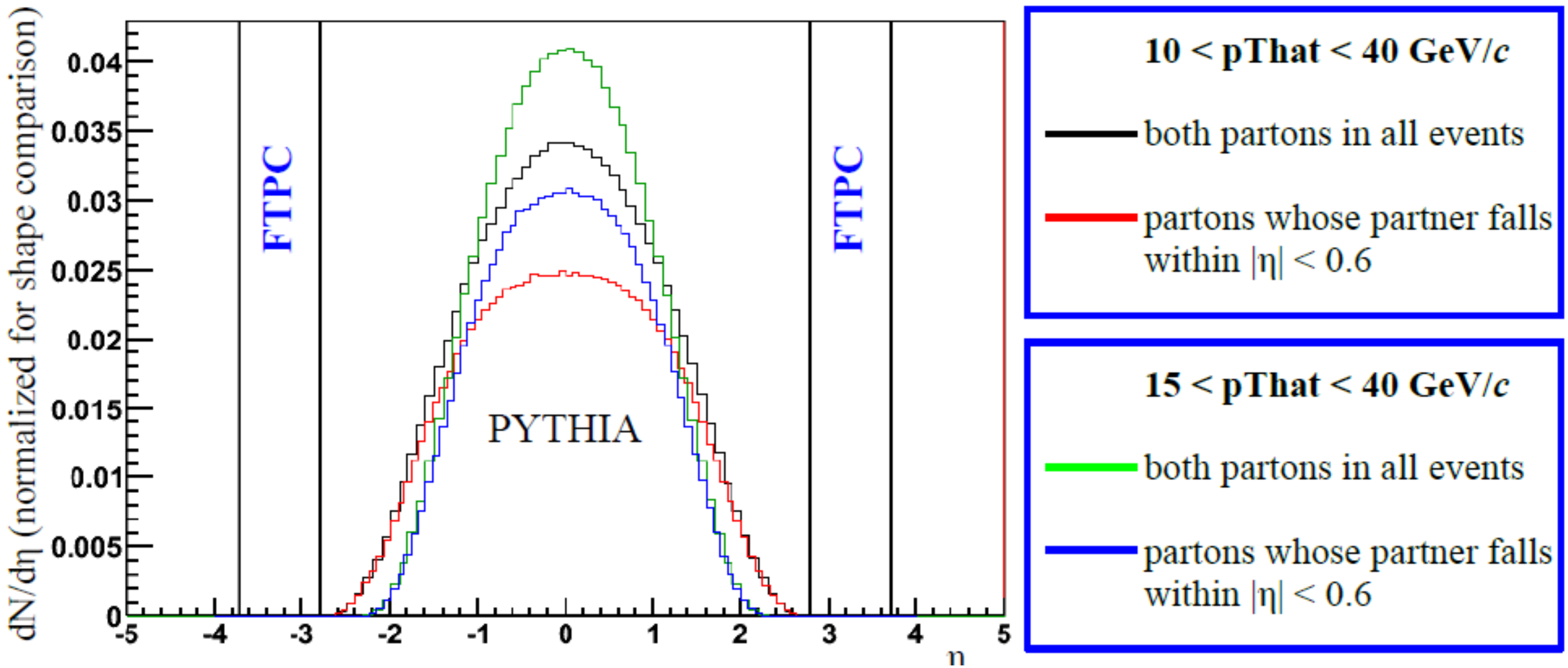
Different rapidity ranges to define centrality → different event samples

Tighter correlation in Au-Au



Different in fluctuations/jet contamination

Does recoil jet hit forward regions?



PYTHIA 2M events:

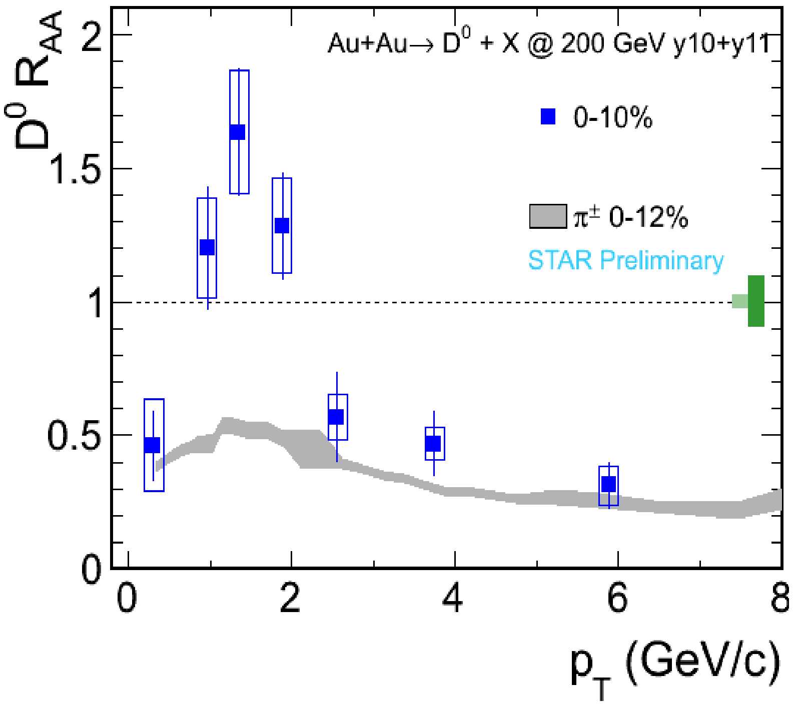
P_{THAT}> 10 GeV: <10 partons in FTPC region

P_{THAT}> 15 GeV: 0 partons in FTPC region

If η>3 for centrality trigger di-jet partner not at mid-rapidity Fluctuations different

Charm suppression

arXiv:1204.4442
arxiv:1207.5445



Similar to light quarks at high p_T

Charm suppression

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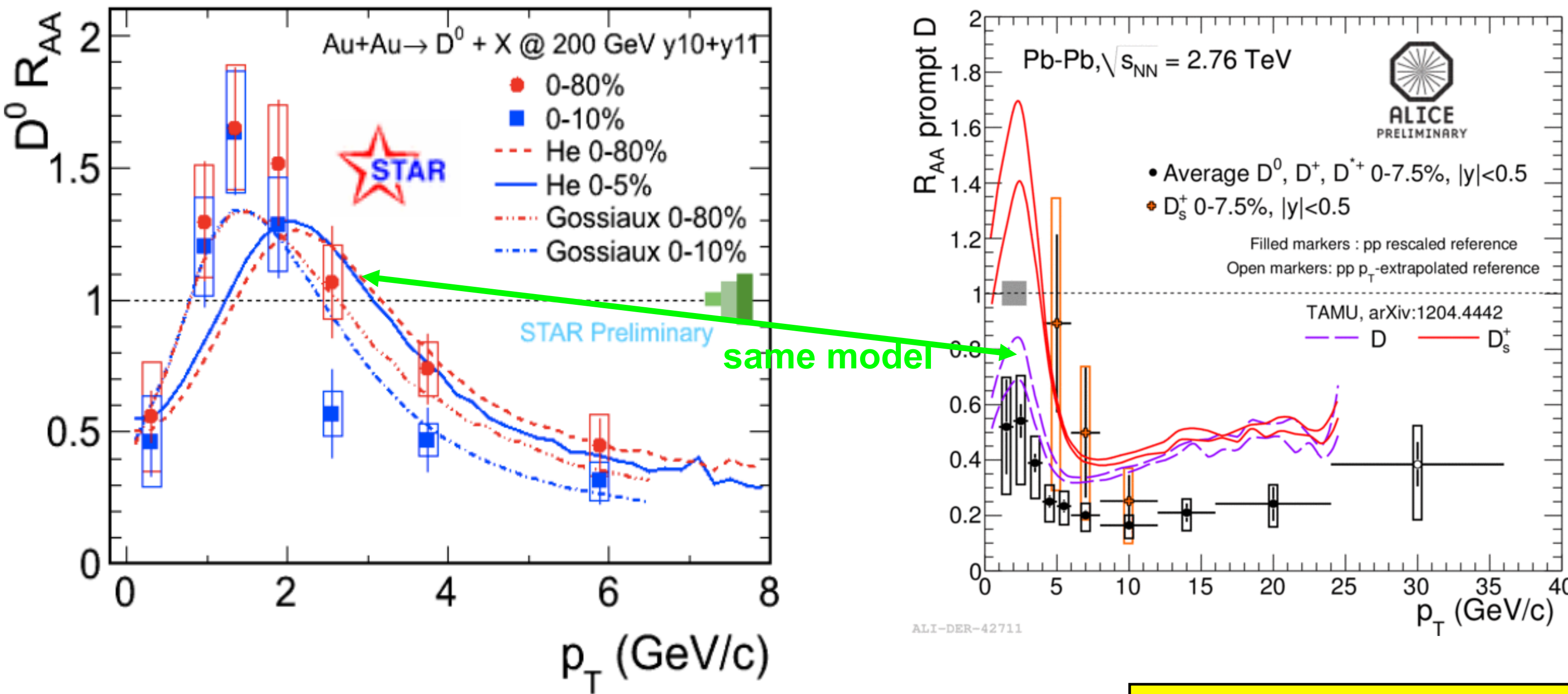


Similar to light quarks at high p_T

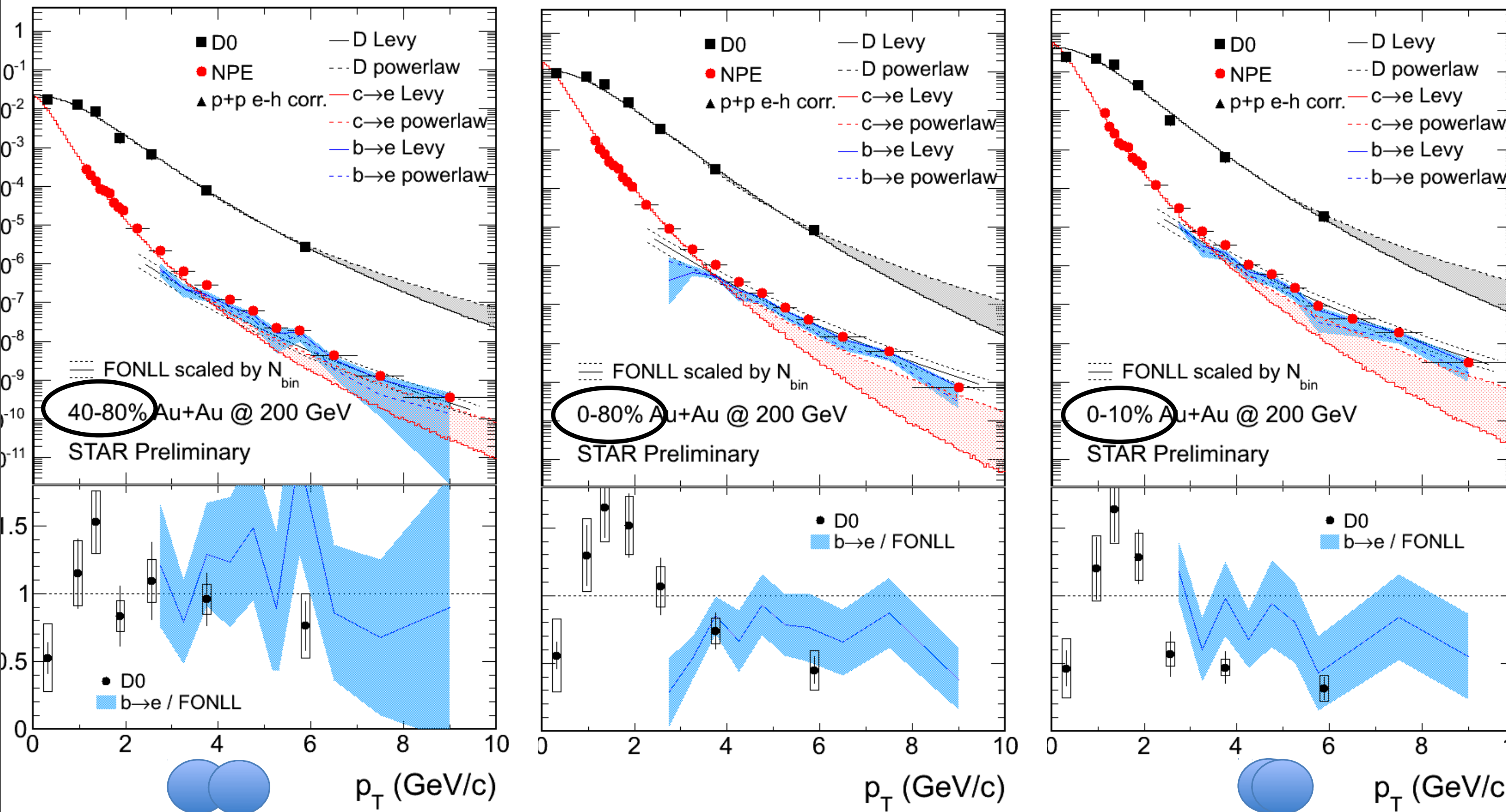
Less suppressed for more peripheral bin

Flow effect stronger at RHIC?
- steeper initial spectrum

At low p_T observe enhancement - reco and/or flow? shadowing?

Same model describes LHC and RHIC

Bottom suppression



Given D and NPE can deduce B suppression

Hint that $R_{AA}^{D} < R_{AA}^{B}$

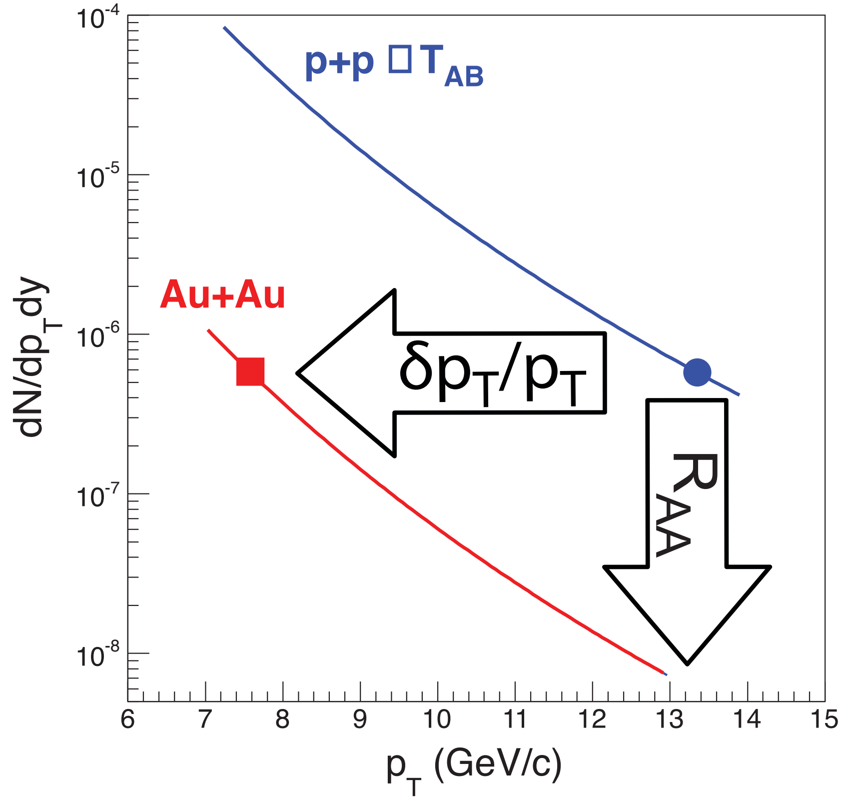
Does this mean less energy loss?

Opaqueness/stopping power of QGP

Measure fractional momentum loss

$\delta p_T/p_T$ instead of R_{AA}

Different $\delta p_T/p_T$ for similar R_{AA}



PRC 87, 034911 (2013)

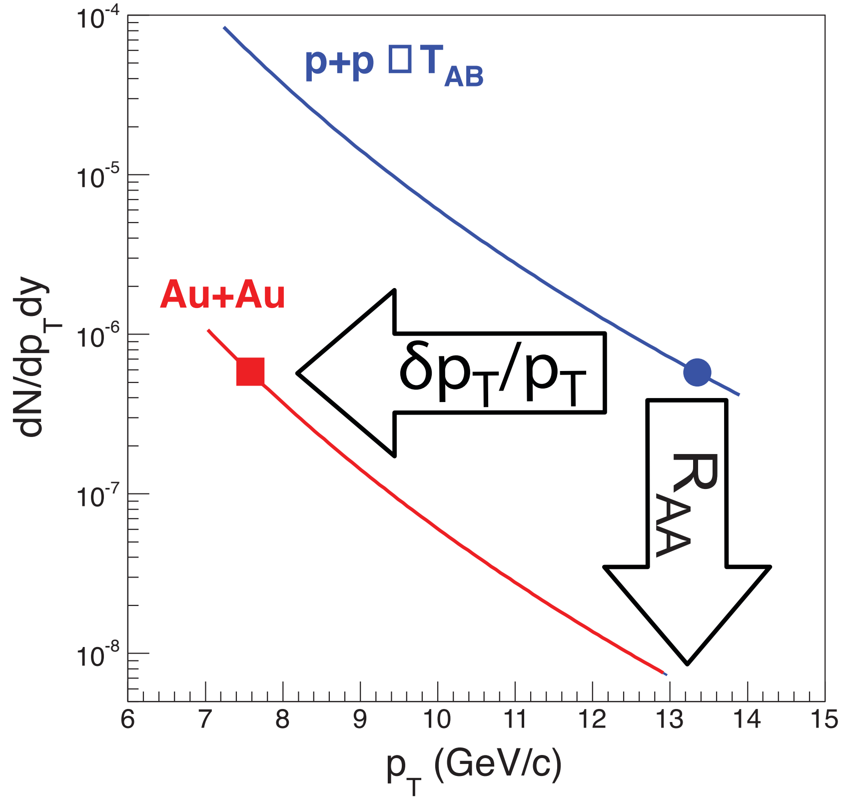
Opaqueness/stopping power of QGP

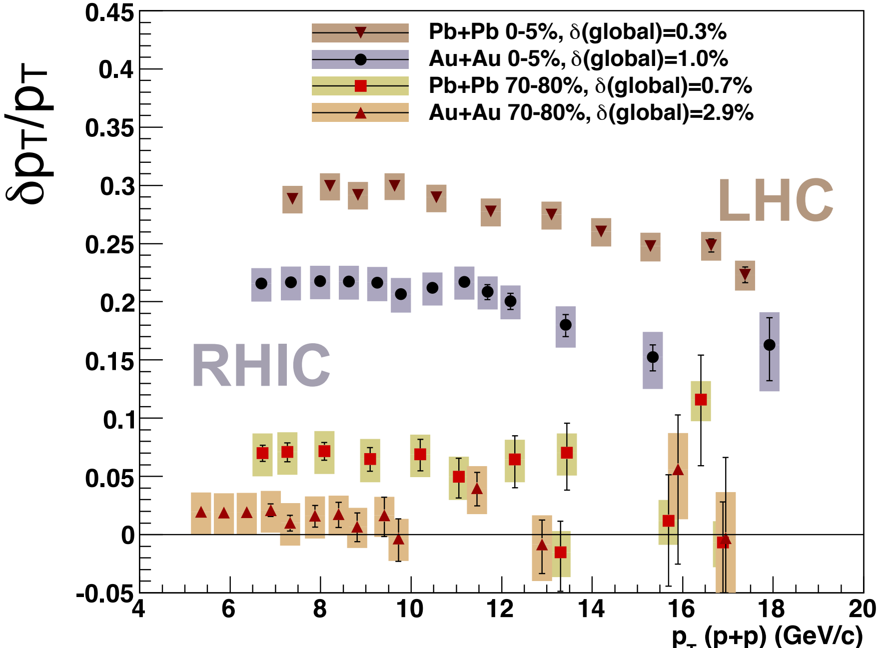
Measure fractional momentum loss

$\delta p_T/p_T$ instead of R_{AA}

Different $\delta p_T/p_T$ for similar R_{AA}

$(\delta p_T)_{LHC} \approx 1.3\ (\delta p_T)_{RHIC}$
but
$(dN/dy)_{LHC} \approx 2.2\ (dN/dy)_{RHIC}$





PRC 87, 034911 (2013)

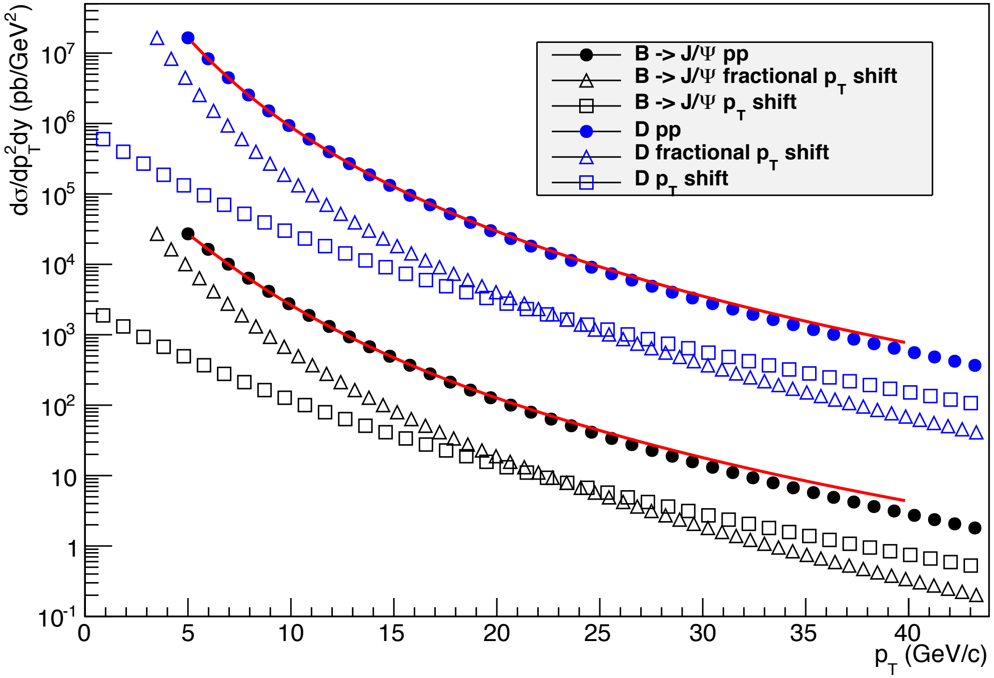
QGP at LHC and RHIC acts differently on hard partons

Smaller δp_T at high p_T

Smaller coupling at LHC?

B vs D R_{AA}: Very simple toy

arXiv:hep-ph/0102134



Using LHC spectra as example

FONLL calc. of B→ J/ψ and D

Assume binary scaling of yield

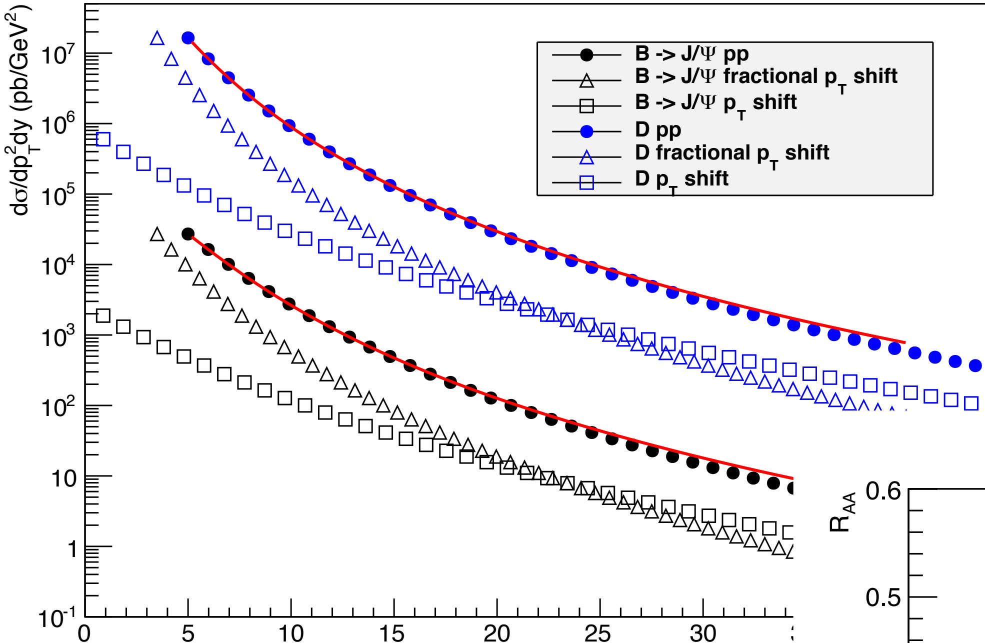
Fit pp spectrum with Tsalis

Then energy loss either:

$\delta p_T/p_T = 0.3$ or $\delta p_T = 10$ GeV/c

B vs D R_{AA}: Very simple toy

arXiv:hep-ph/0102134



Using LHC spectra as example

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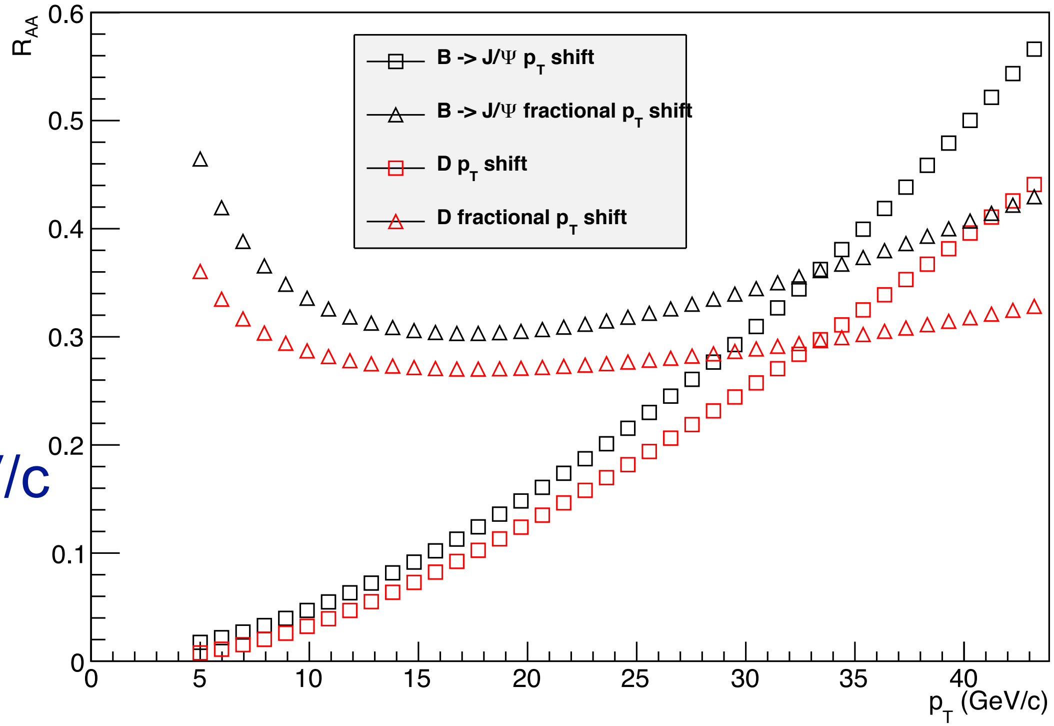
Then energy loss either:

$\delta p_T/p_T = 0.3$ or $\delta p_T = 10$ GeV/c

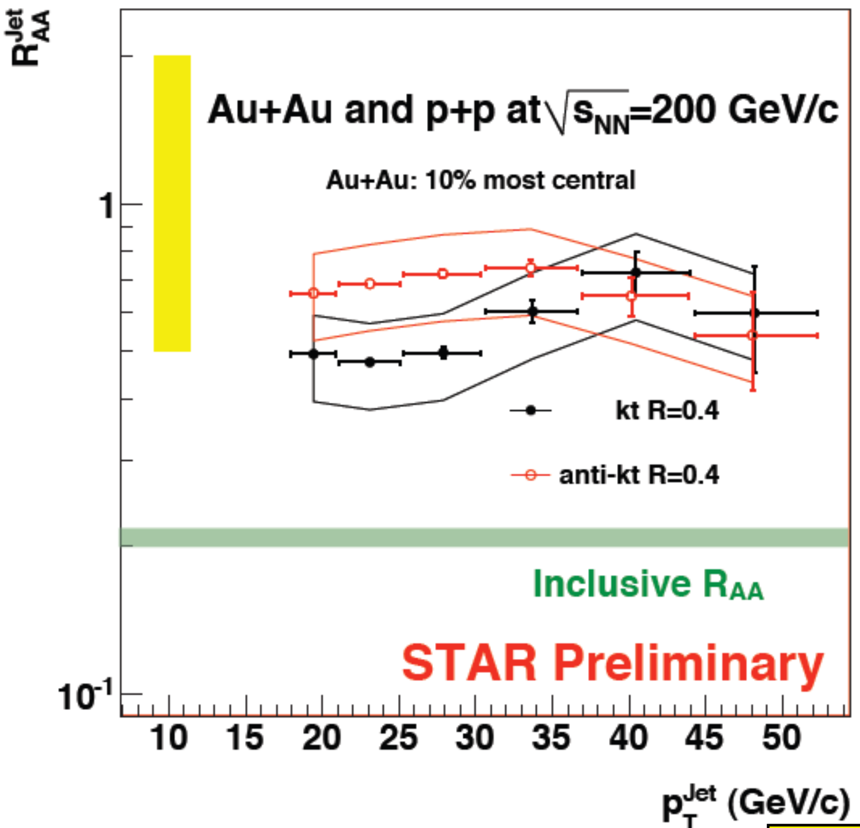
$\delta p_T/p_T = 0.3$ ~ trend of data

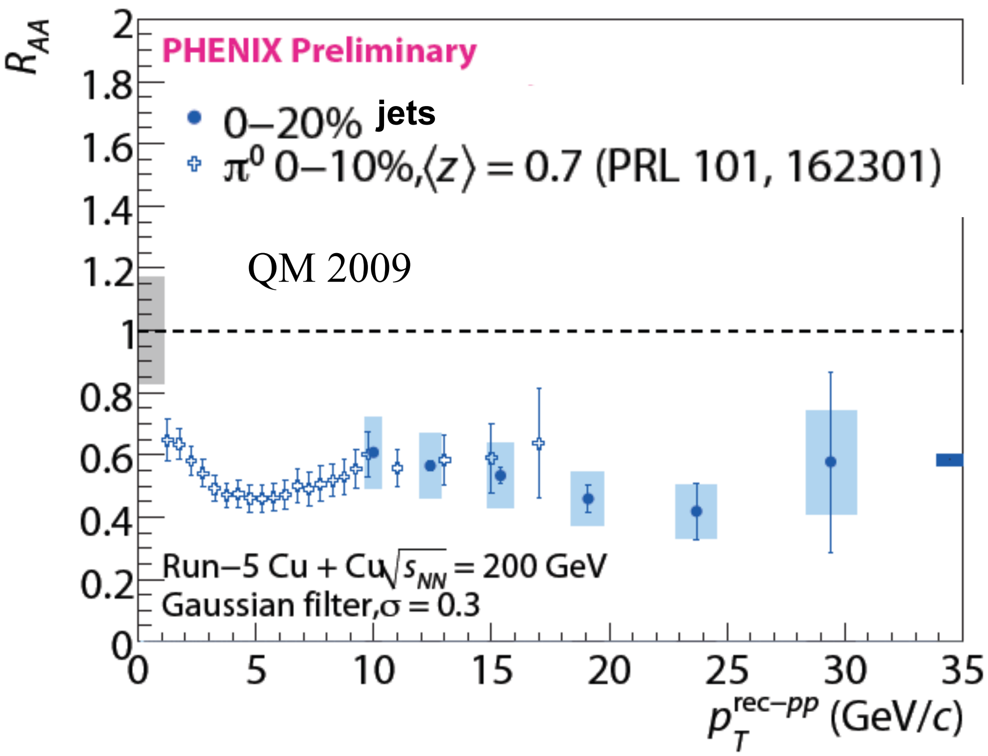
$R_{AA}^D < R_{AA}^B$



Jet R_{AA} at RHIC

- Suppression even of jets demonstrated in 2009 - first jets in HI collisions
- Differing techniques make comparisons difficult
- Work continued at LHC improved understanding of backgrounds, fluctuations, unfolding, biases

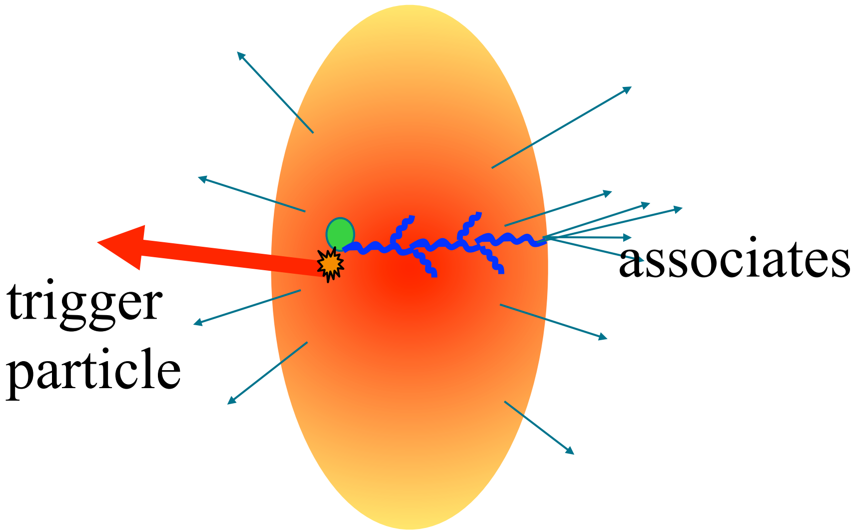


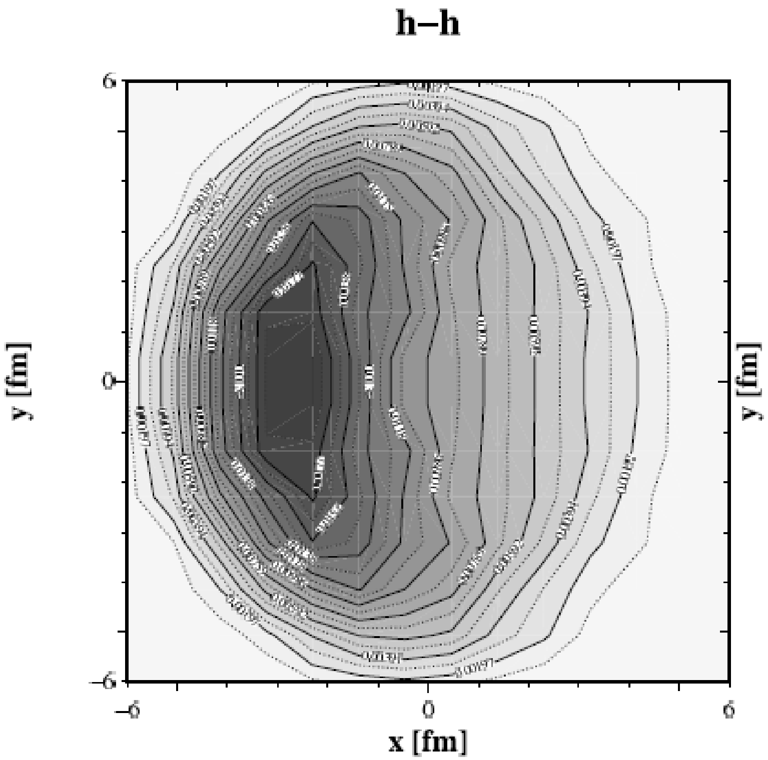


New results with higher stats. in the works

hadron-hadron correlations

YaJEM-DE-MC





Some surface bias

d-Au mid-rapidity correlation functions

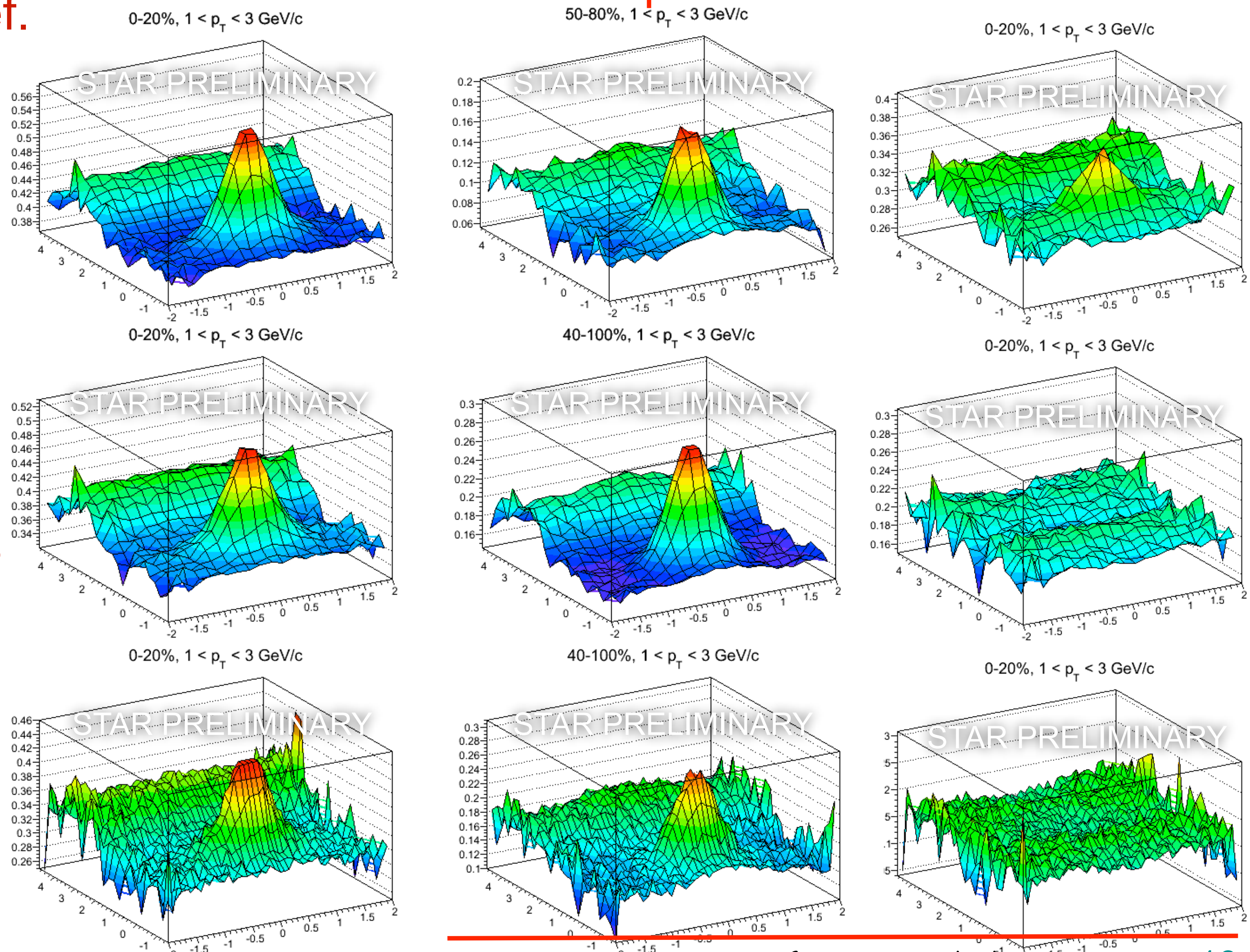
$1 < p_T^{trig}, p_T^{assoc} < 3$ GeV/c

Centrality def. | Central | Peripheral | Difference

TPC mult. $|\eta|<1$

FTPC-E (Au-side) $-3.8<\eta<-2.8$

ZDC-E (Au-side)

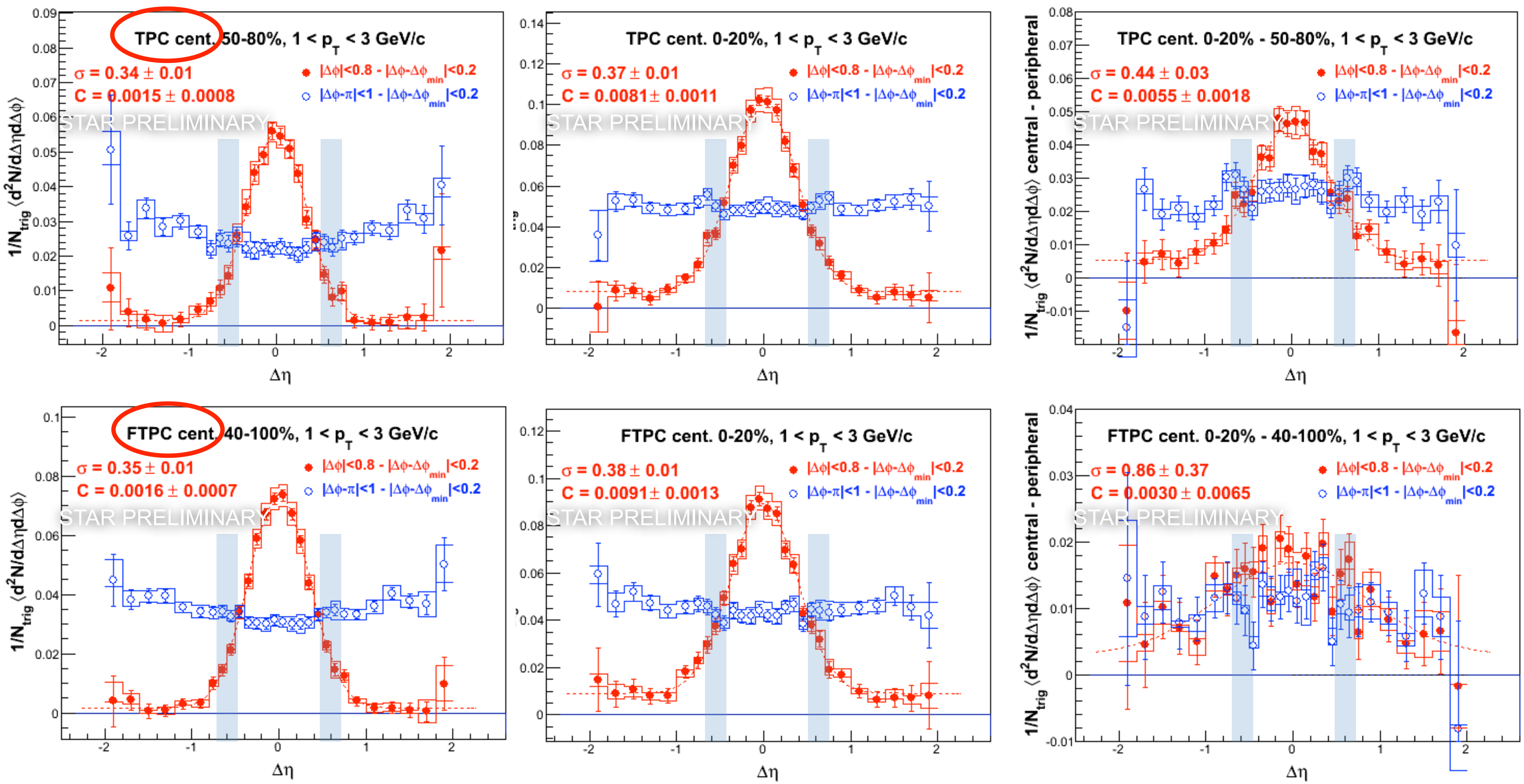


Δη correlations, ZYAM'ed

Shaded: PHENIX acceptance

ZYAM-ed

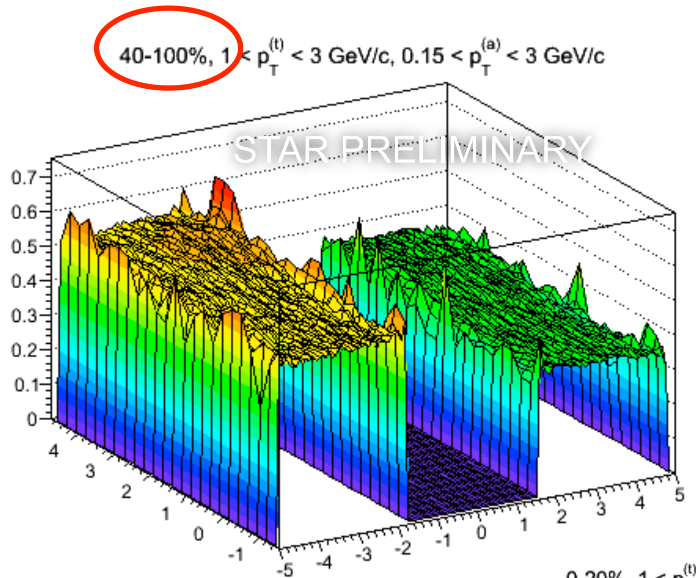
$1 < p_T^{trig}, p_T^{assoc} < 3$ GeV/c

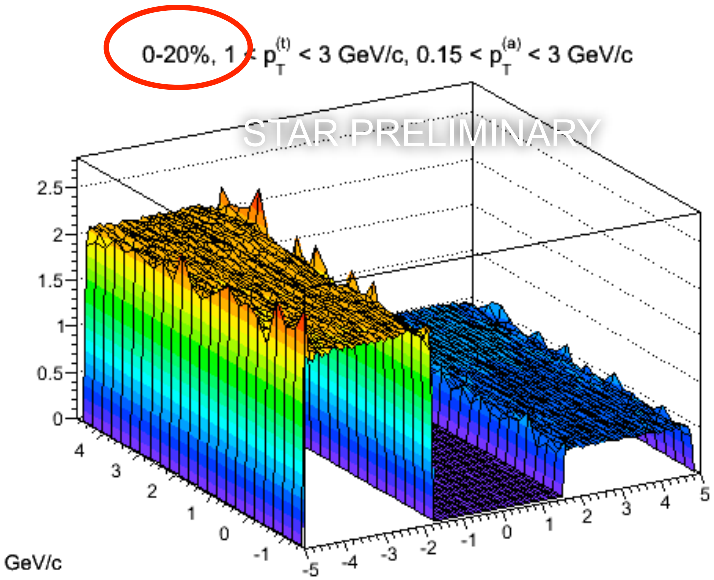


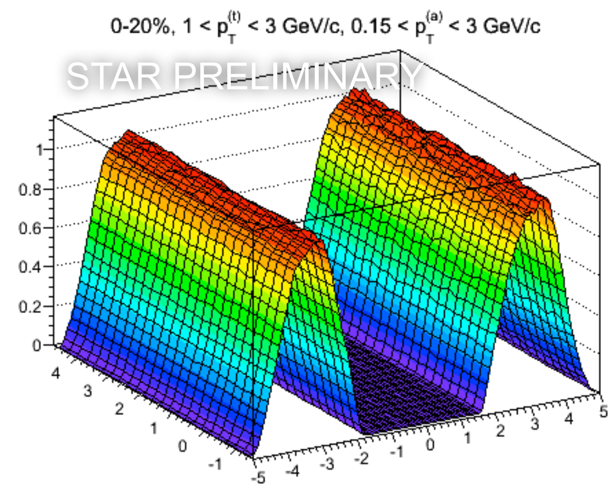
ZYAM syst. error from different sizes of Δφ region for ZYAM.

Reasonable agreement between experiments with same cuts

d-Au TPC-FTPC correlations







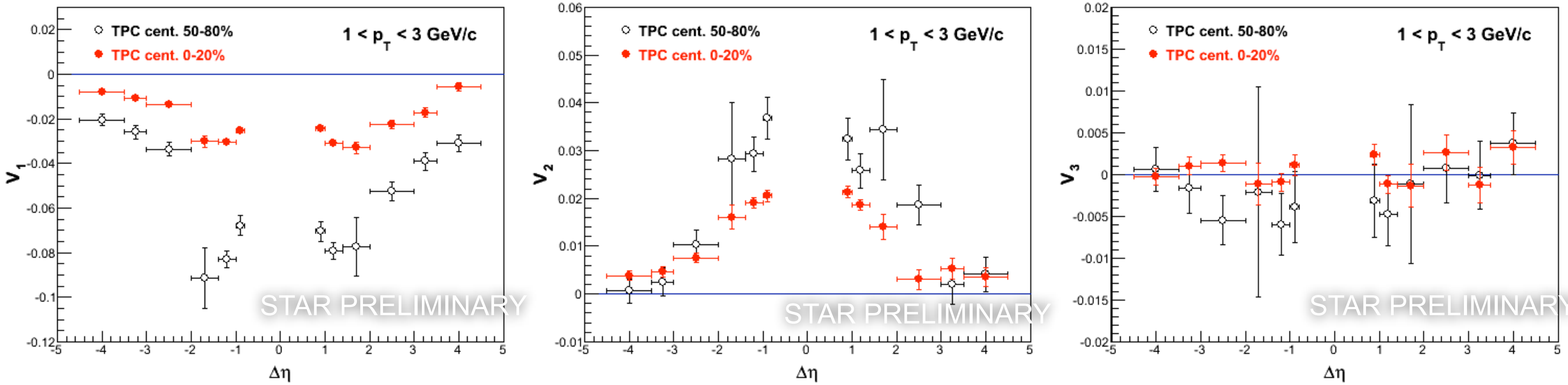
$\Delta\eta$ triangle acceptance

Extend study to larger $\Delta\eta$

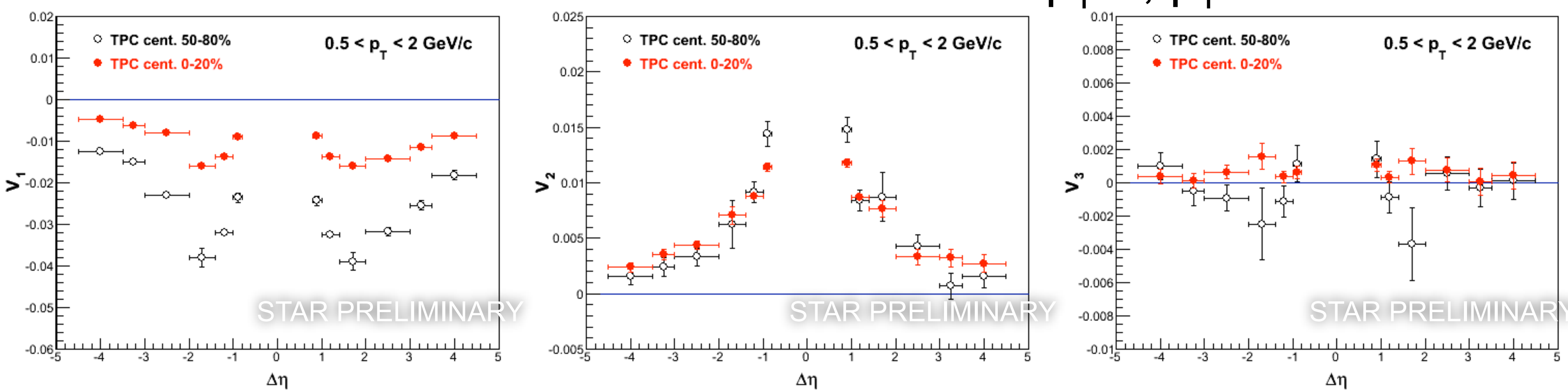
Calculated Fourier Coefficents

$$V_n = \langle \cos(n\Delta\phi) \rangle$$

$1 < p_T^{trig}, p_T^{assoc} < 3$ GeV/c



$0.5 < p_T^{trig}, p_T^{assoc} < 2$ GeV/c

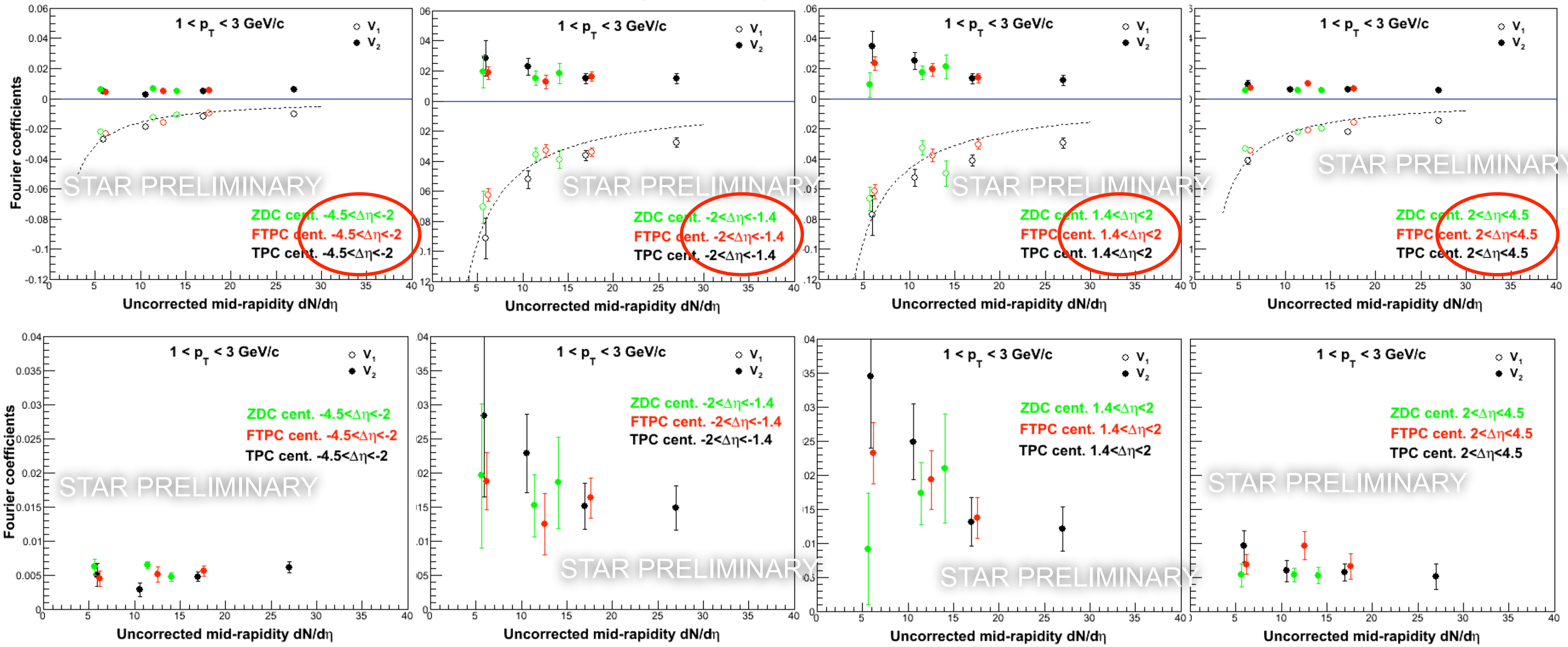


Strong dependence of V_1 and V_2 on $\Delta\eta$

Strong dependence of V_1 on mult.

Calculated Fourier coefficients

$1 < p_T^{trig}, p_T^{assoc} < 3$ GeV/c



Au-side ⟷ **d-side**

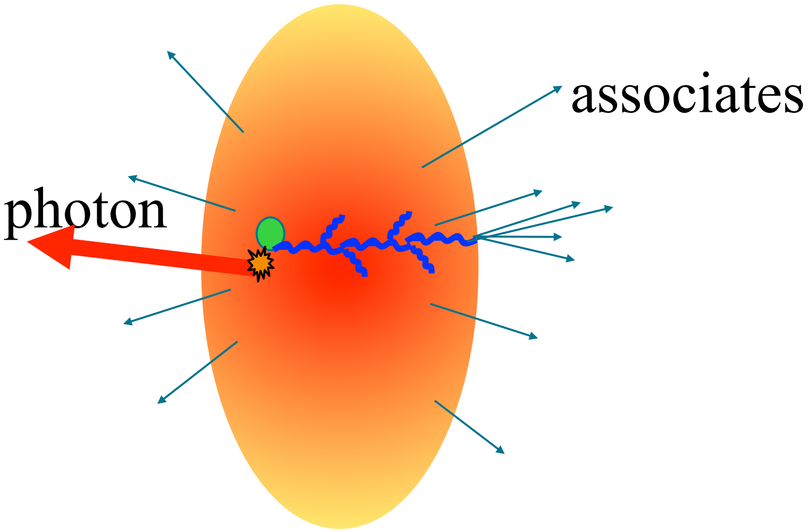
Correlations have V_1 and V_2 components

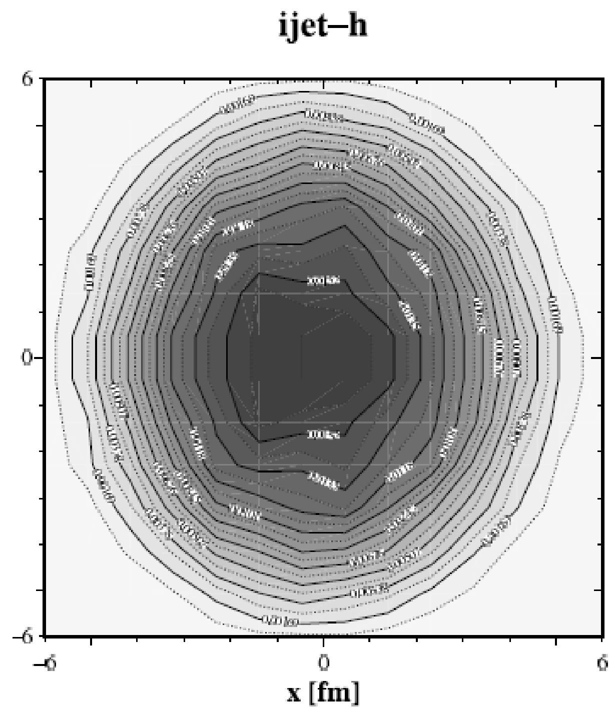
V_1 appears ~1/N. V_2 ~constant over multiplicity

Even at very forward d-side, V_2 component is large (maybe even larger than Au-side).

γ-hadron correlations

YaJEM-DE-MC



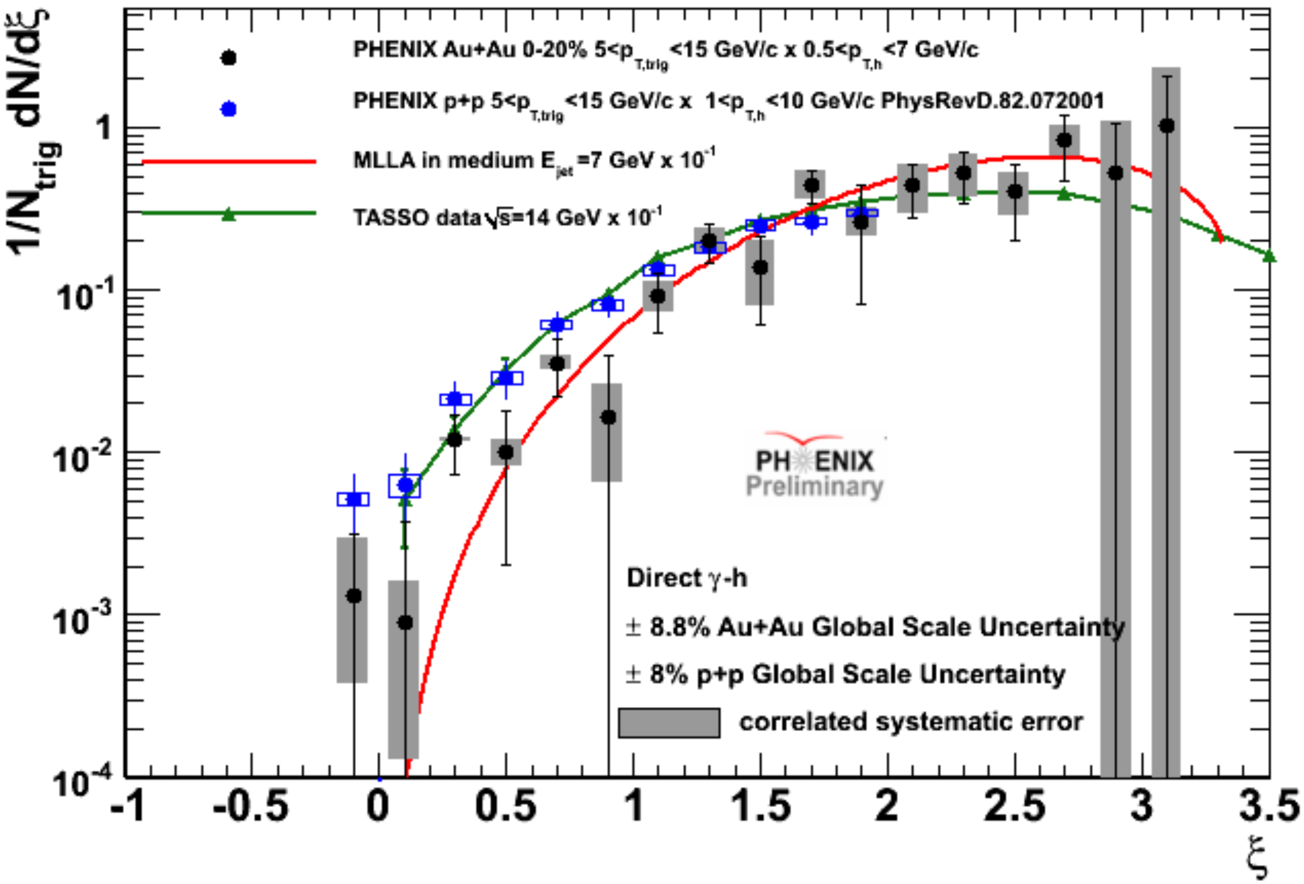


γ-jet pairs produced in q+g → q+γ

Photons do not lose energy in the medium, $p_T^{photon} \approx p_T^{parton}$

Little/No surface bias

γ-hadron



$\xi = \ln(1/z_T)$

$z_T = p_T^{hadron}/p_T^{photon}$

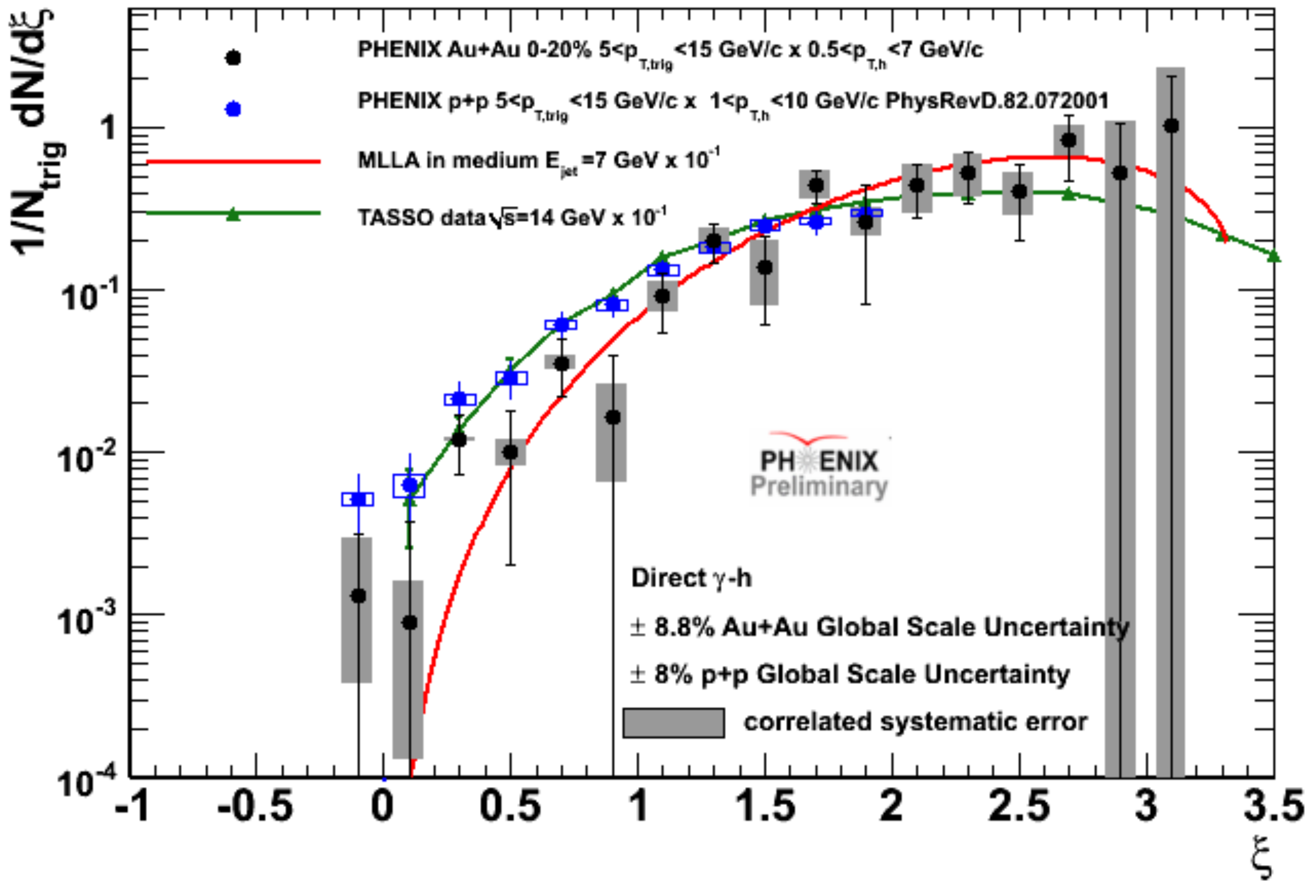
Unbiased recoil jet modified

pp data compare well to TASSO data

Softening of recoil jet fragmentation in central Au-Au events

γ-hadron

arXiv:1212.3323



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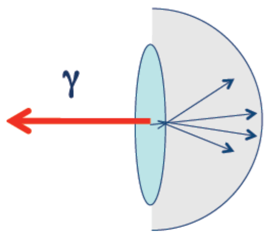
Softening of recoil jet fragmentation in central Au-Au events

Where does the energy go?

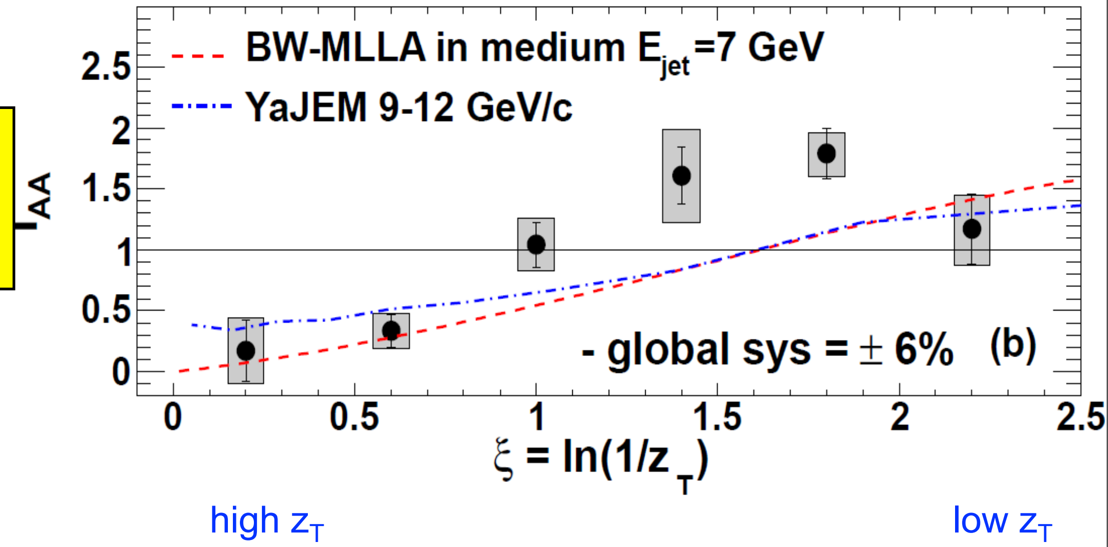
arXiv:1212.3323

γ - Energy calibration
I_{AA} as function of "cone R"

$$I_{AA} = \frac{\text{yield in Au+Au}}{\text{yield in p+p}}$$



"Lost" hard particles emerge as multiple soft particles



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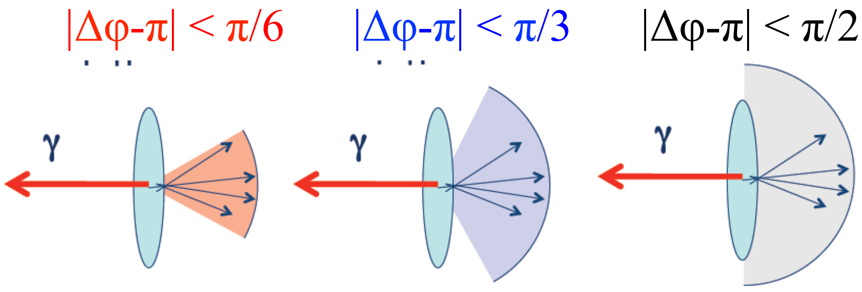
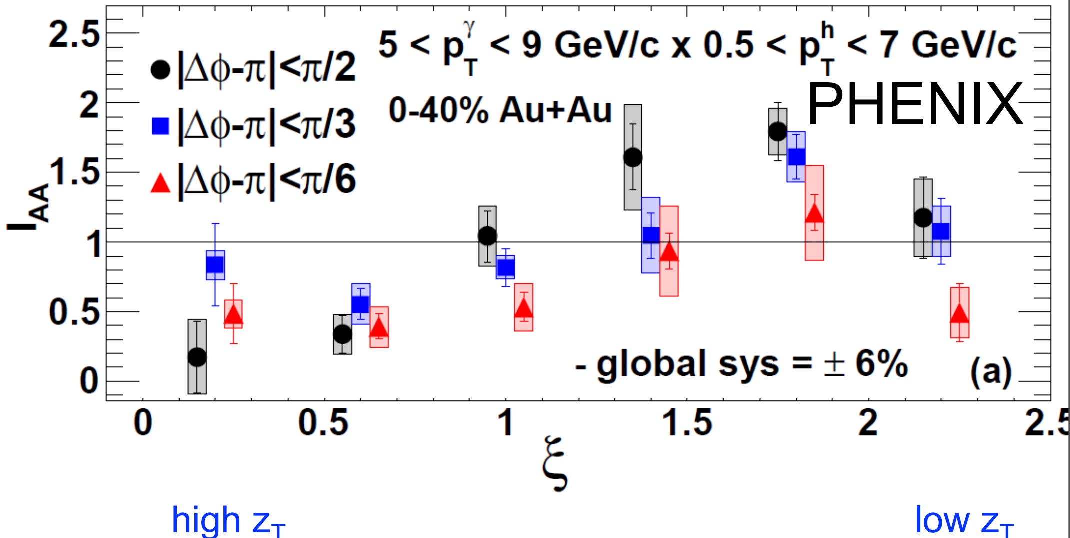


$$I_{AA} = \frac{\text{yield in Au+Au}}{\text{yield in p+p}}$$



"Lost" hard particles emerge as multiple soft particles

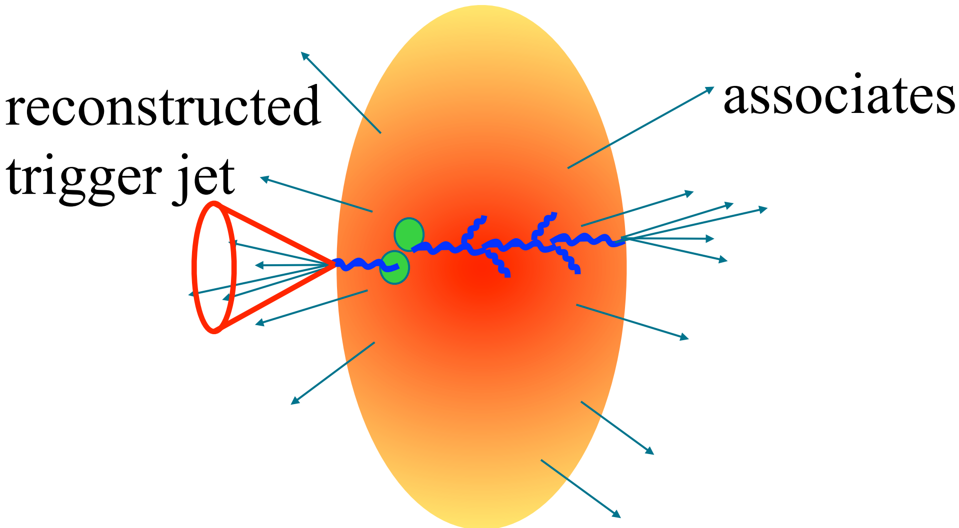
In narrow cone (|Δφ-π| < π/6 (R~0.5)):

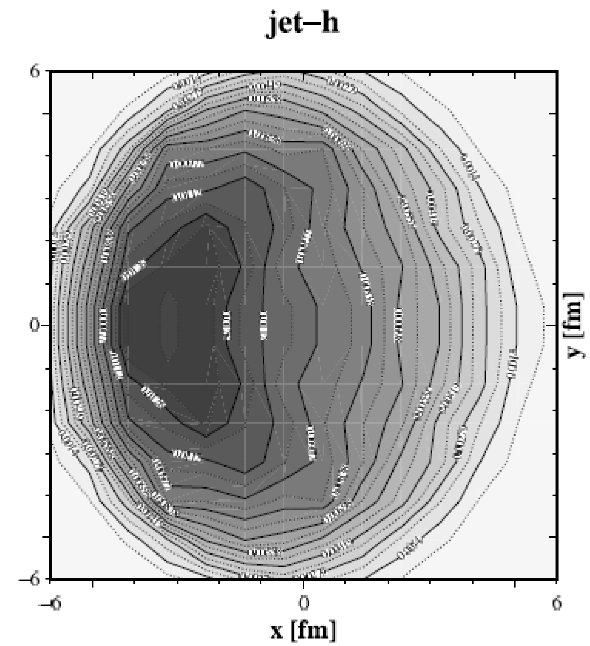
high-z_T hadrons "lost", no corresponding "gain" at low z_T

soft particles at large angles

Jet-hadron correlations

YaJEM-DE-MC

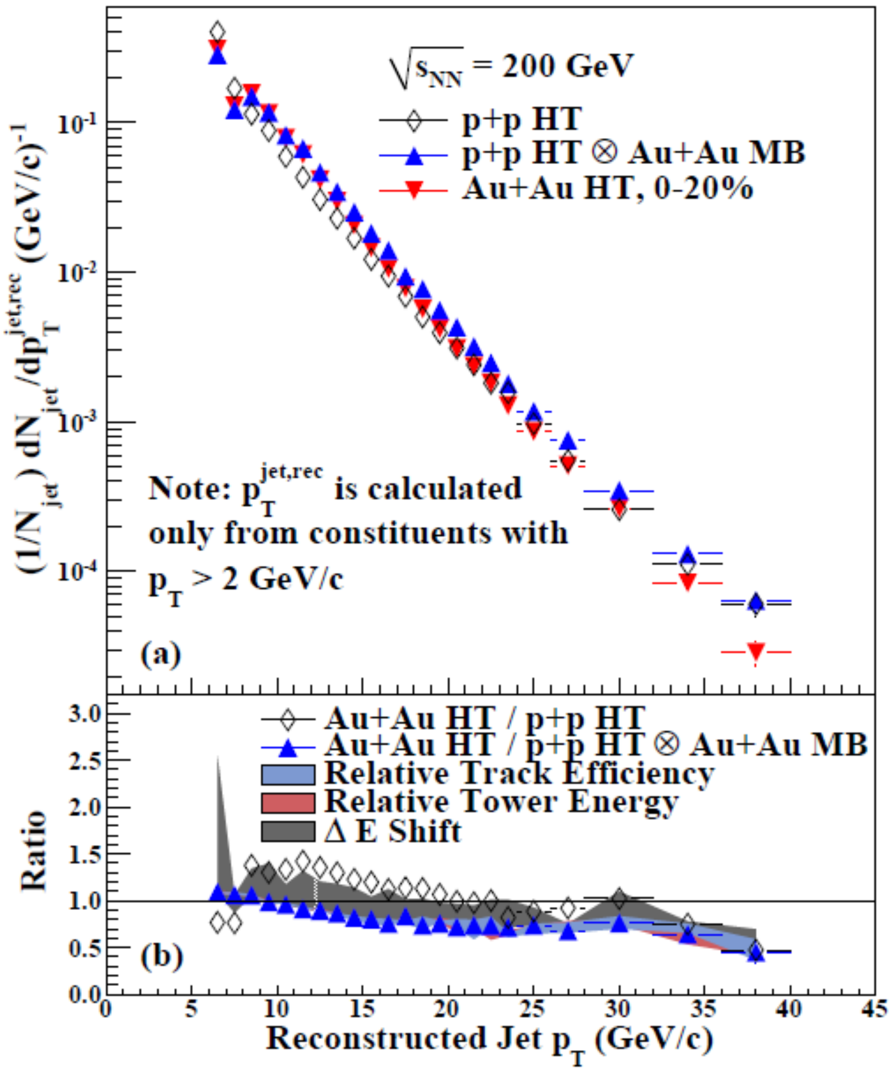




Jet surface biased by trigger selection, $p_{Tjet}^{AA} \sim p_{Tjet}^{pp} != p_{Tparton}$

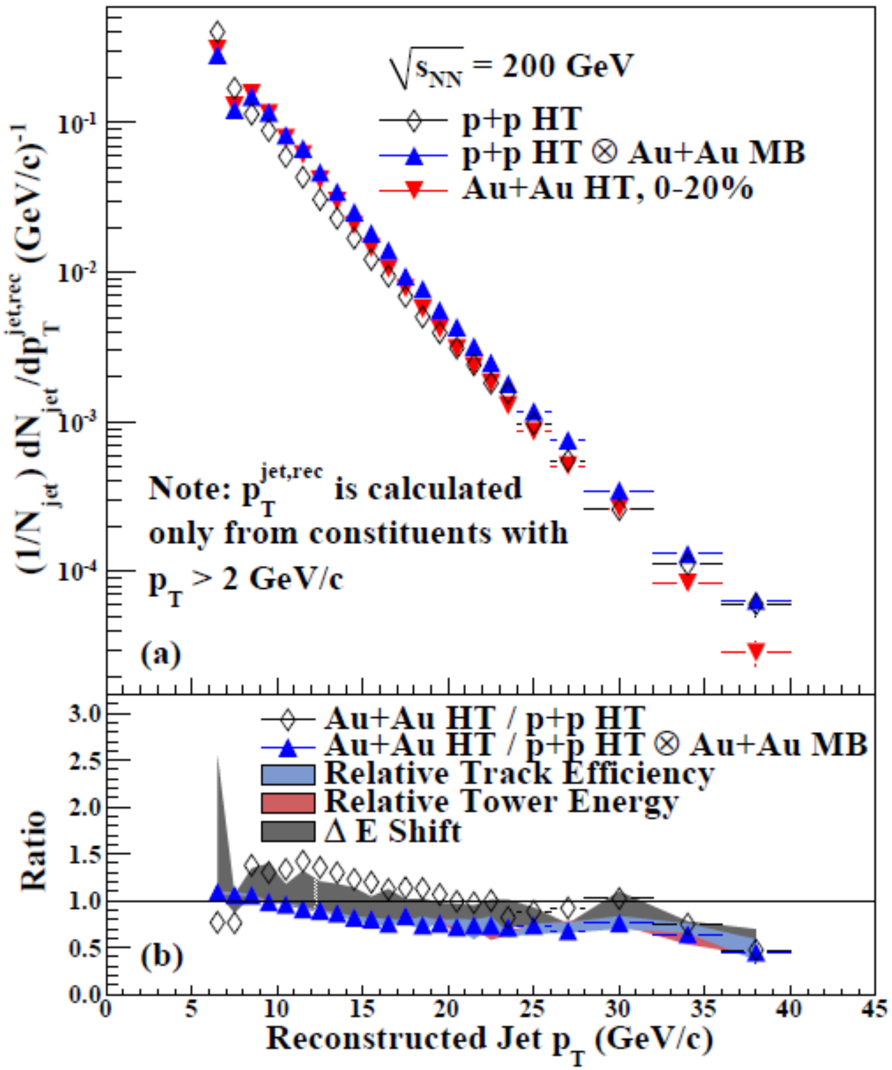
Extreme surface bias

Jet-hadron correlations



Au-Au trigger jet spectra (and correlations) look like pp

Jet-hadron correlations



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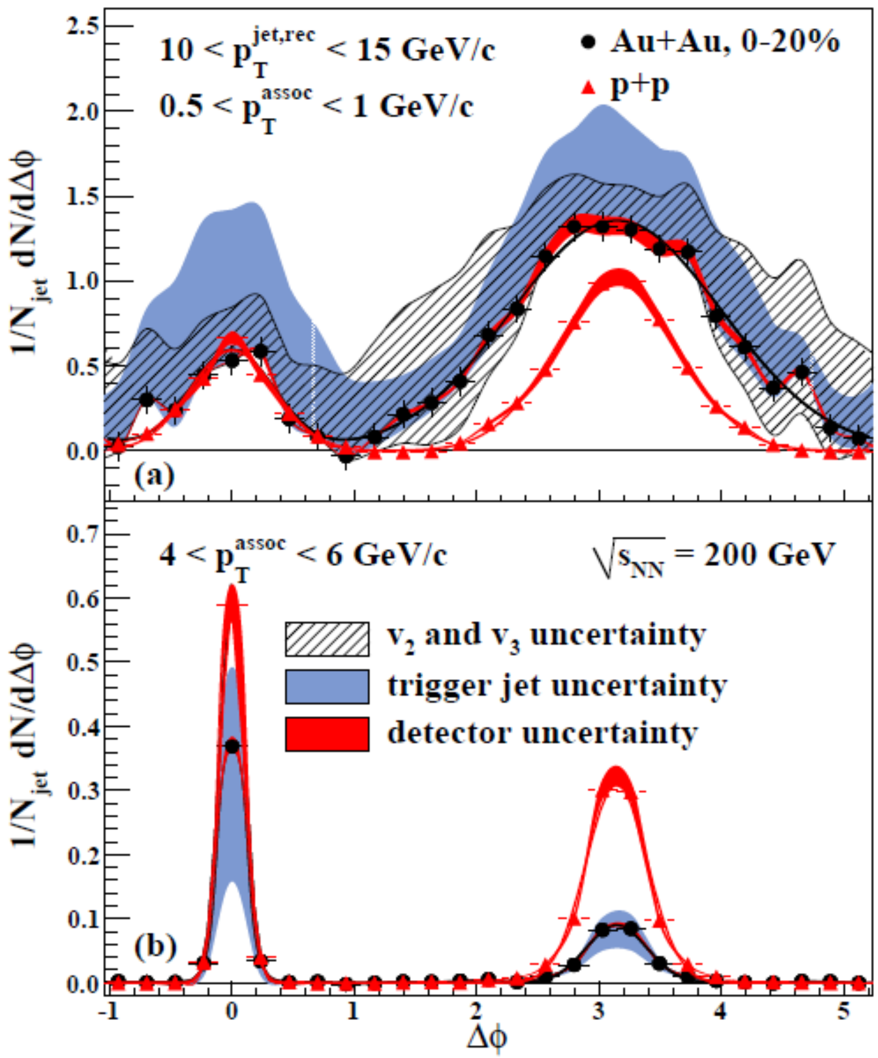
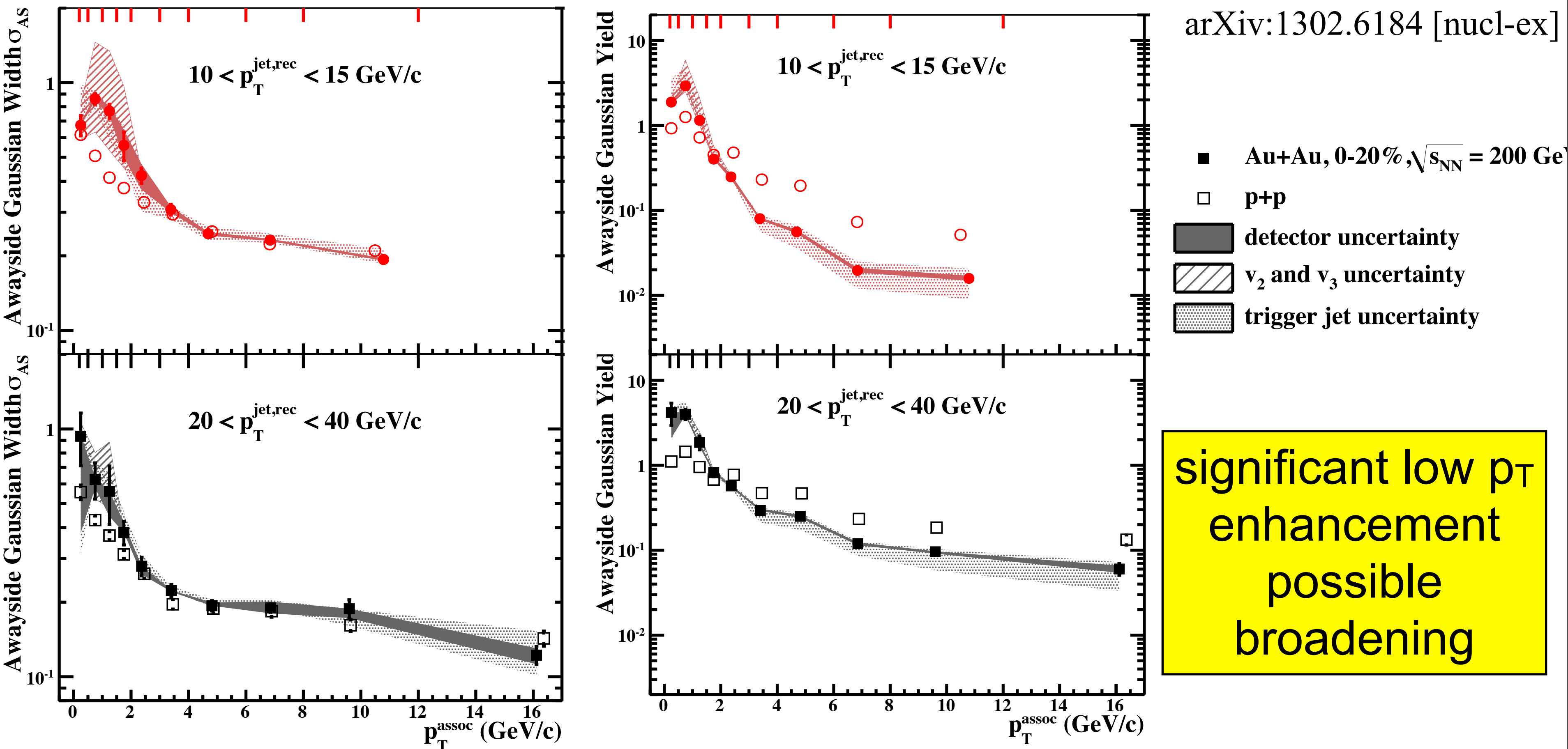


High p_T suppression,
Low p_T enhancement

Awayside Gaussian widths and yields



arXiv:1302.6184 [nucl-ex]

significant low p_T enhancement possible broadening

Widths suggest jet broadening at low-p_T (but highly-dependent on v_3)

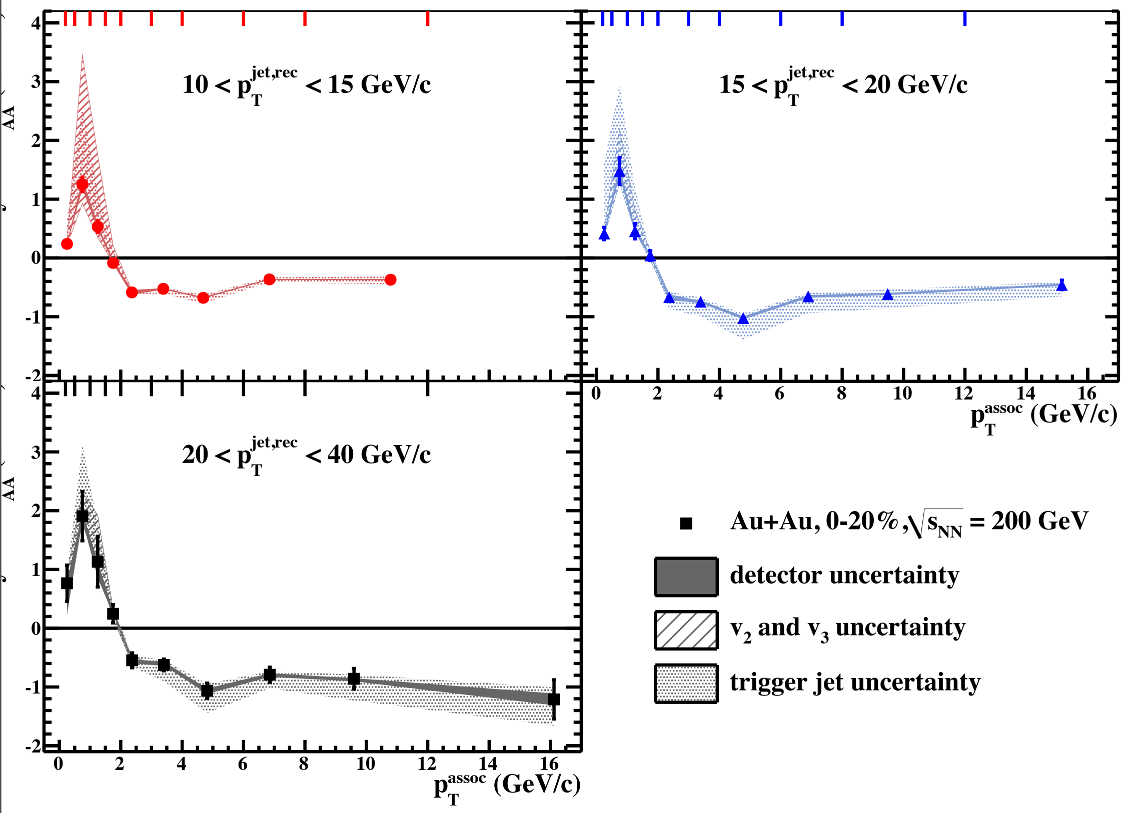
Further information is needed about v_2^{jet}, v_3^{jet} (possible correlation of jets with reaction plane / participant planes)…

Awayside energy balance

arXiv:1302.6184 [nucl-ex]

$$D_{AA}(p_T^{assoc}) = Y_{AuAu}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{AuAu} - Y_{pp}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{pp}$$

$$\Delta B = \sum_{p_T^{assoc}\text{ bins}} D_{AA}(p_T^{assoc})$$



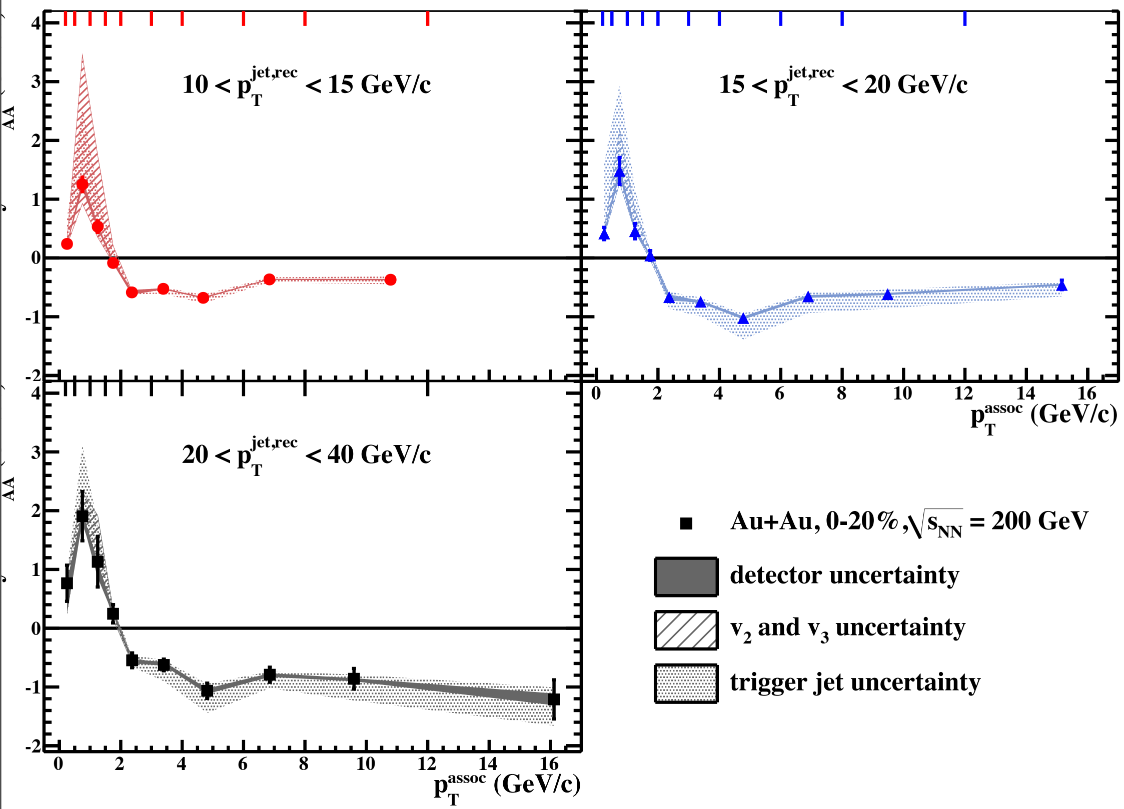
$p_T^{jet,rec}$ (GeV/c)	ΔB p_T> 2GeV/c (GeV/c)
10-15	-2.5
15-20	-4.2
20-40	-5.1

Awayside energy balance

arXiv:1302.6184 [nucl-ex]

$$D_{AA}(p_T^{assoc}) = Y_{AuAu}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{AuAu} - Y_{pp}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{pp}$$

$$\Delta B = \sum_{p_T^{assoc} \text{ bins}} D_{AA}(p_T^{assoc})$$



$p_T^{jet,rec}$ (GeV/c)	ΔB p_T> 2GeV/c (GeV/c)
10-15	-2.5
15-20	-4.2
20-40	-5.1

$p_T^{jet,rec}$ (GeV/c)	ΔB (GeV/c)			
10-15	-0.6 ± 0.2	$^{+0.2}_{-0.2}$	$^{+3.7}_{-0.5}$	$^{+2.3}_{-0.0}$
15-20	-1.8 ± 0.3	$^{+0.3}_{-0.3}$	$^{+1.0}_{-0.0}$	$^{+1.9}_{-0.0}$
20-40	-1.0 ± 0.8	$^{+0.1}_{-0.8}$	$^{+1.2}_{-0.1}$	$^{+0.3}_{-0.0}$

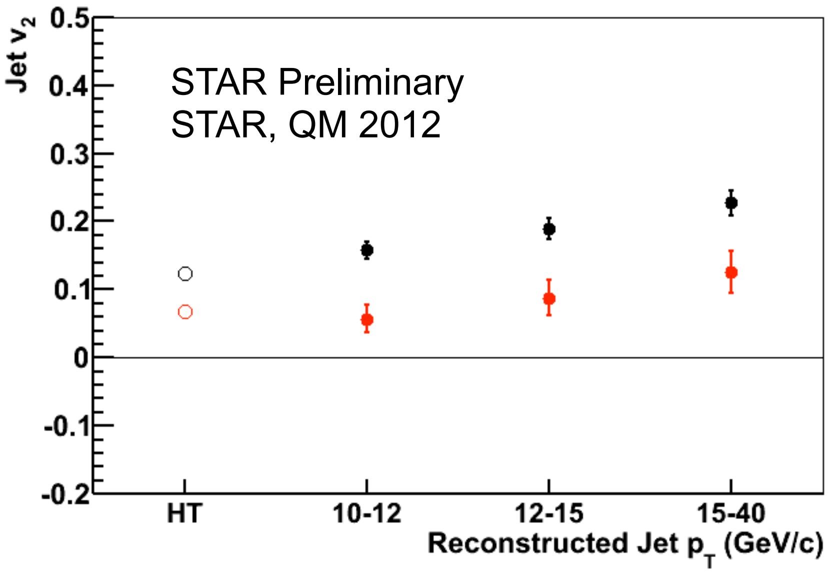
Near perfect energy balance when integrate over all p_T and jet correlation

Uncertainties due to:
detector effects
v_2 and v_3
jet energy scale

Jet v_2 at STAR

Correlation between jet axis and event plane

$$v_2^{jet} = \frac{\left\langle \cos\left(2(\Psi_{jet} - \Psi_{EP})\right)\right\rangle}{R}$$

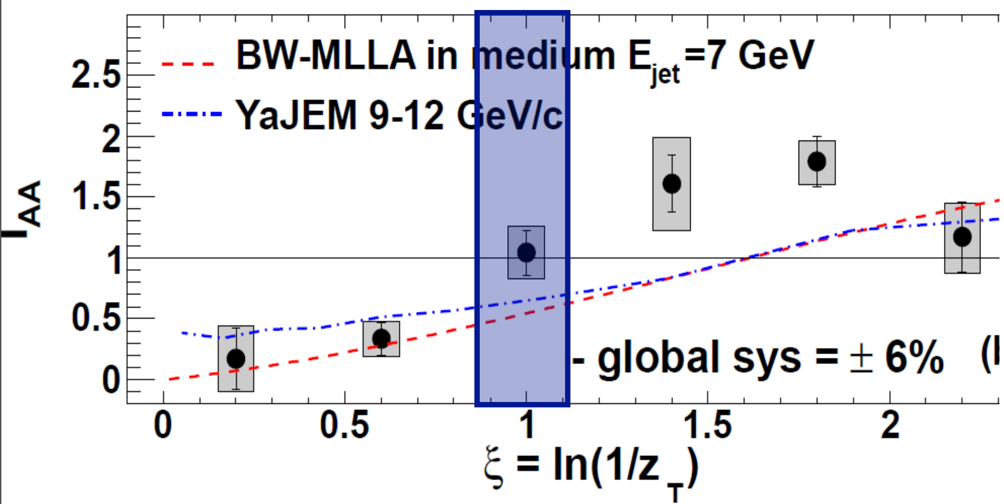


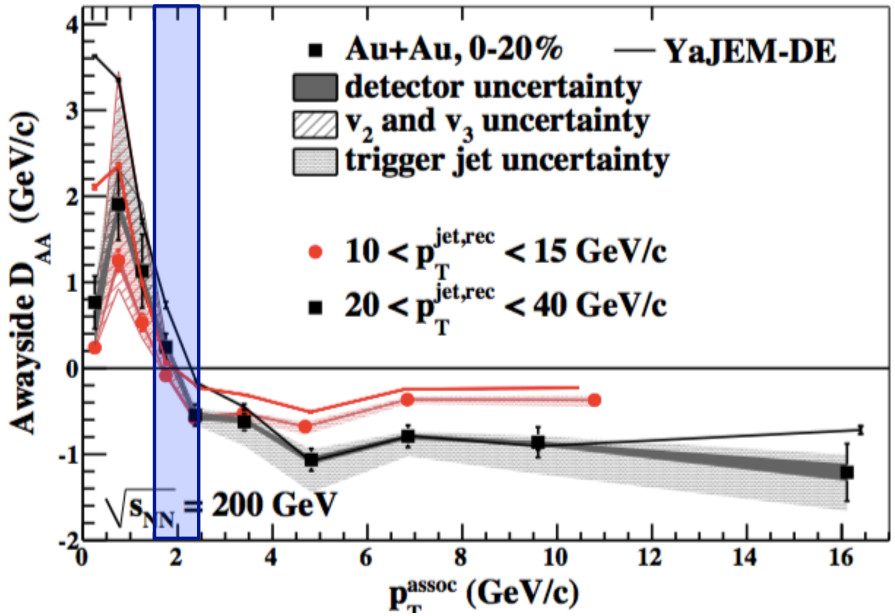
Jet Definition:
HT trigger E_T > 5.5 GeV
constituent p_T^{cut} = 2 GeV/*c*
$|\eta_{jet}| < 0.6$

- ● v_2 {TPC EP} ($|\eta| < 1$)
- ● v_2 {TPC EP} ($2.8 < |\eta| < 3.7$)

Jet v_2{FTPC EP} is non-zero
→ more jets reconstructed in-plane than out-of-plane
→ evidence of pathlength-dependence of parton energy loss
Jet v_2 ≈ HT v_2 → bias towards unmodified jets largely driven by HT requirement

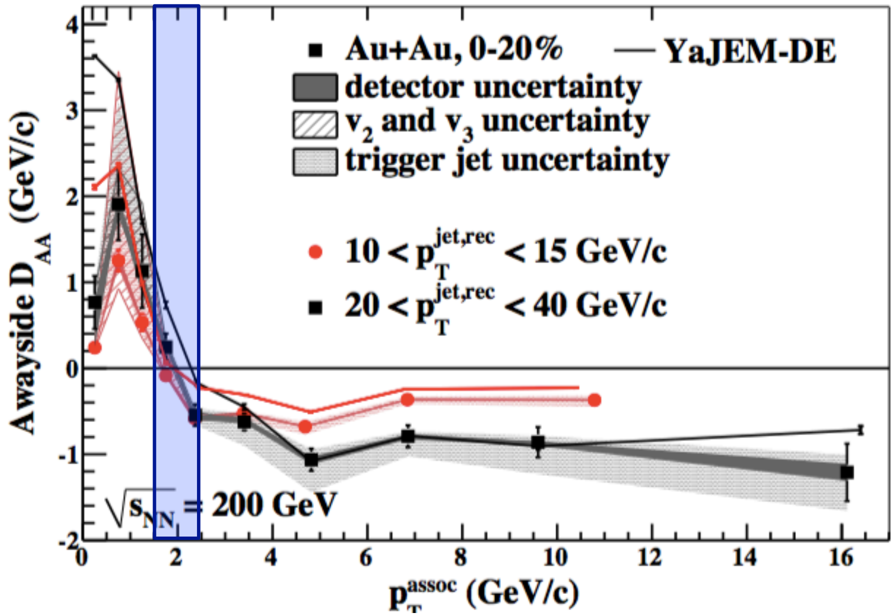
Where do enhancement turn on?





At RHIC switch from suppression to enhancement occurs at ~2 GeV/c

Where do enhancement turn on?



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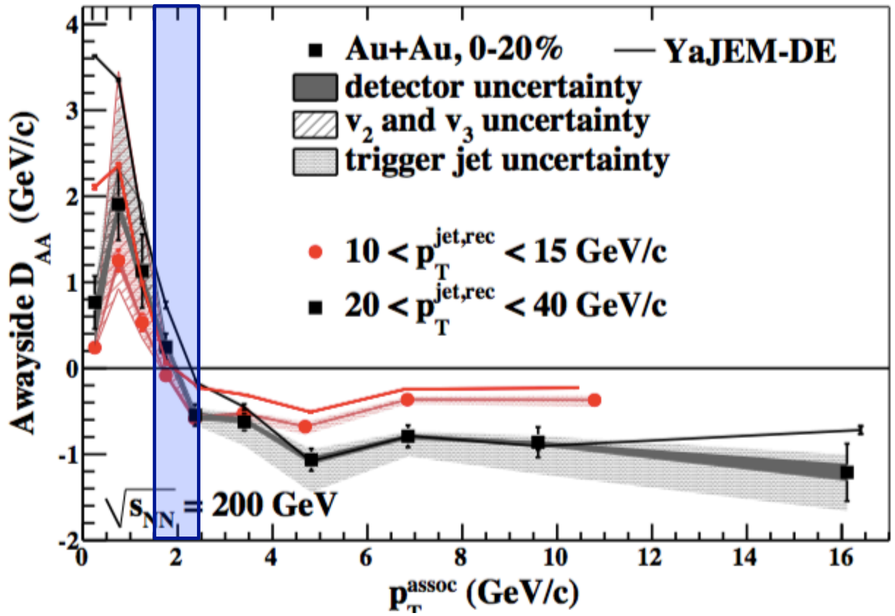
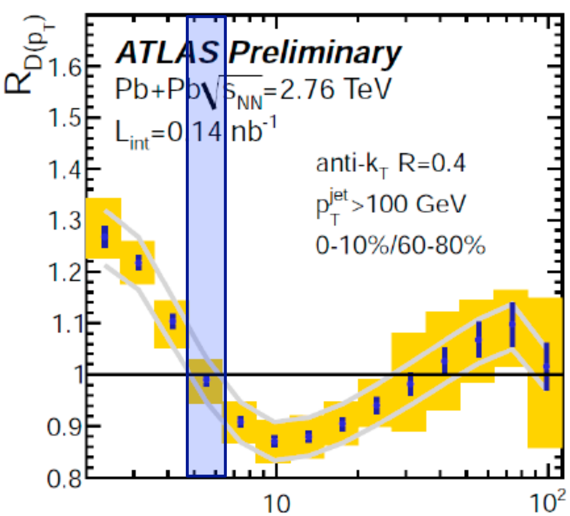
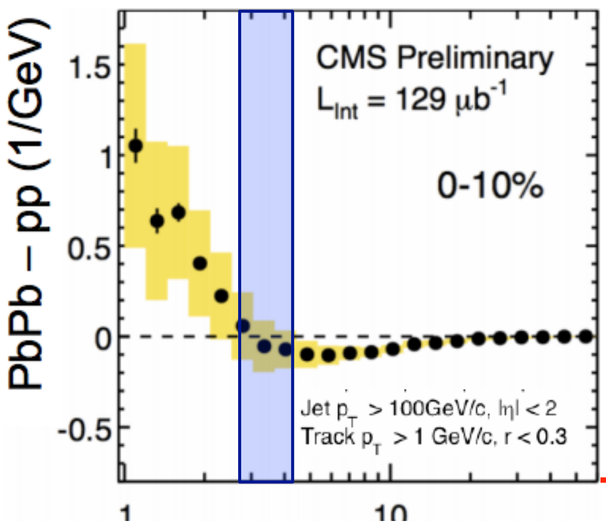


At RHIC switch from suppression to enhancement occurs at ~2 GeV/c

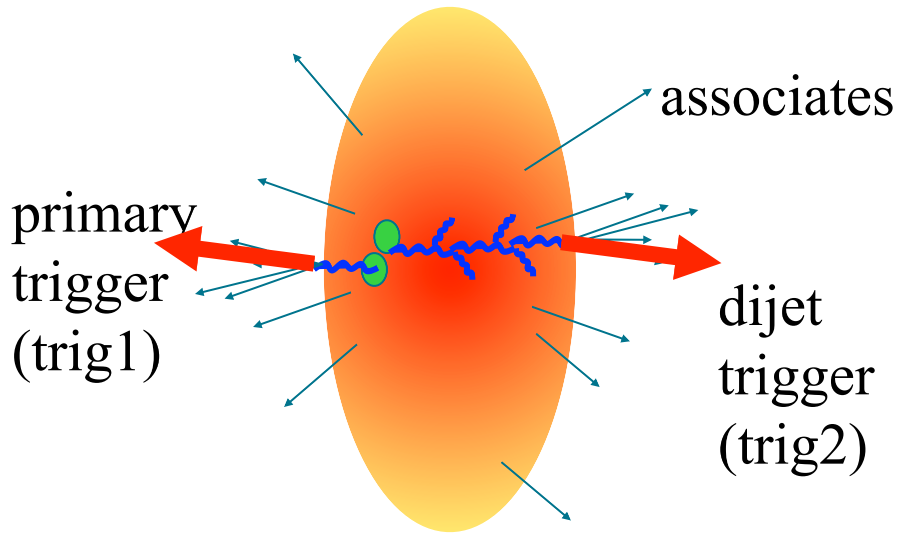




At LHC switch to enhancement occurs at ~4 GeV/c

Due to different "jet" energies?

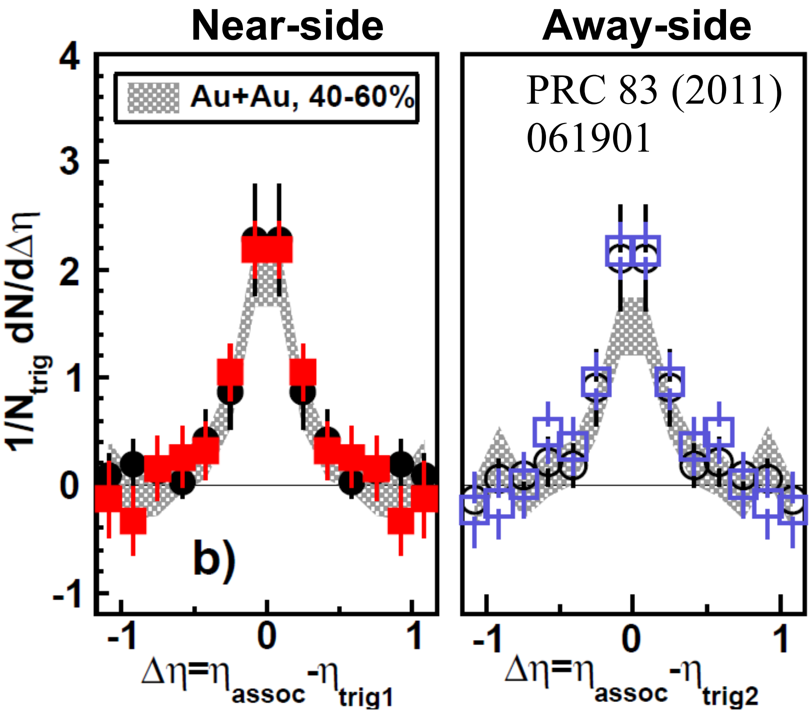
2+1 correlations



Require back-to-back high p_T triggers

Enhances possibility of tangential jets

Symmetric triggers



■ Au+Au
● d+Au

$5 < p_T^{trig1} < 10$ GeV/c

$4 < p_T^{trig2} < p_T^{trig1}$

1.5 GeV/c $< p_T^{assoc} < p_T^{trig1}$

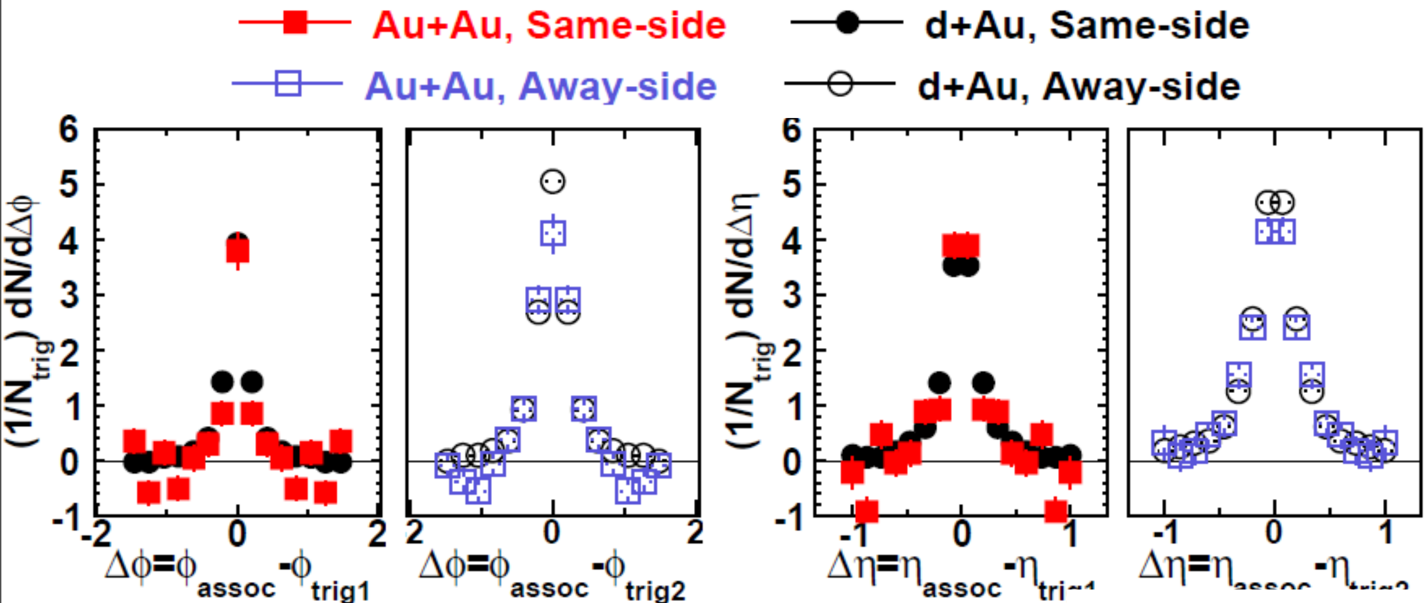
No significant difference between Au+Au and d+Au

No significant difference between near-side and away-side.

Are we sampling surface-biased/unmodified dijets? Or dijets in which both jets lose similar amounts of energy?

Asymmetric triggers

PRC 87 (2013) 44903



$10 < E_T^{trig1} < 15$ GeV (BEMC)

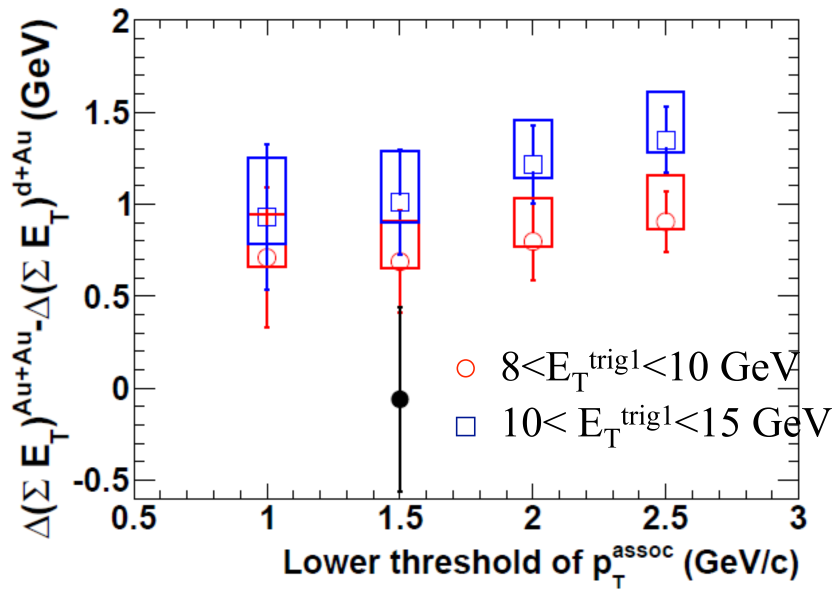
$4 < p_T^{trig2} < 10$ GeV/c (TPC)

$1 < p_T^{assoc} < 10$ GeV/c

Still no large shape difference:

near- vs away-sides

Au-Au vs d-Au



Relative dijet imbalance

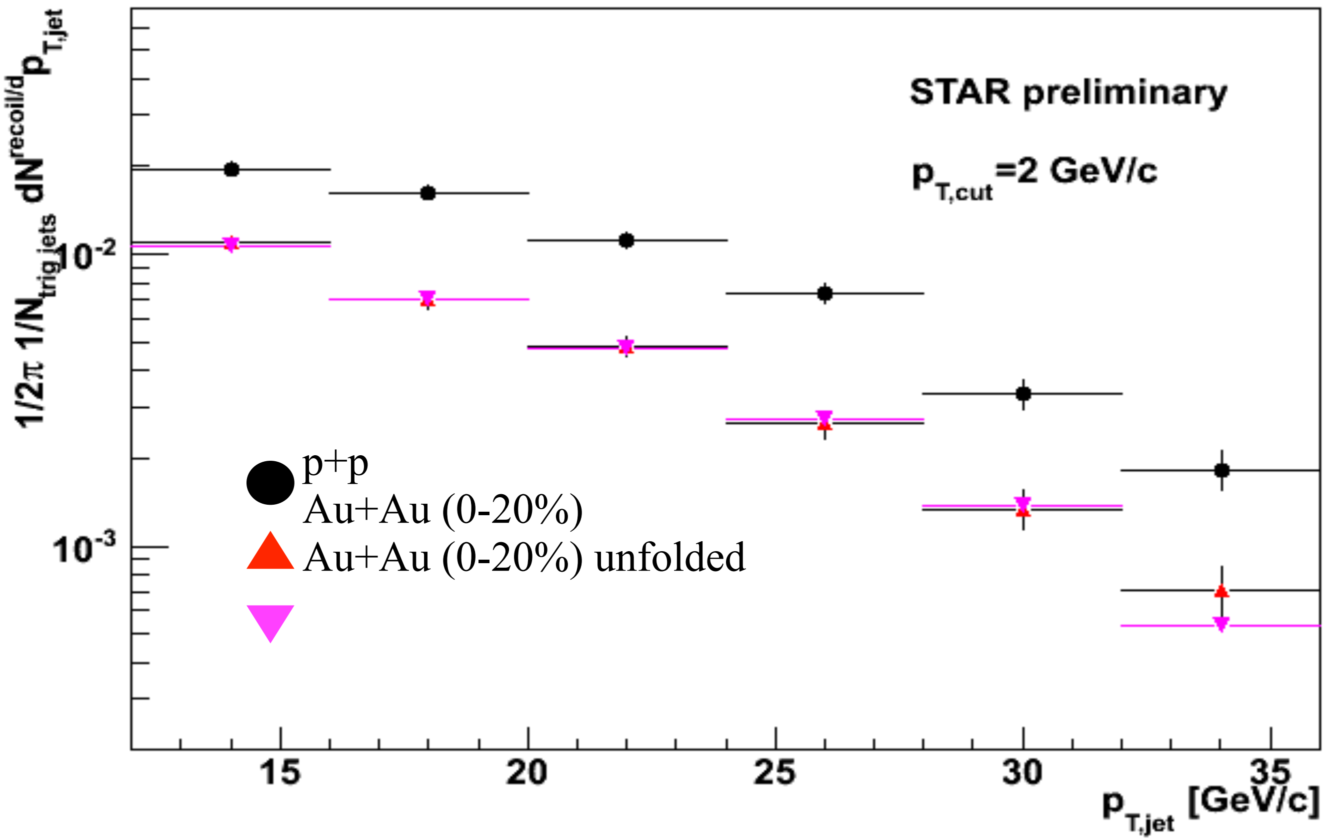
$\Delta(\Sigma E_T)^{Au\text{-}Au} - \Delta(\Sigma E_T)^{d\text{-}Au}$

Dijet imbalance indicates slight softening of away-side peak

Di-jet coincidence rate

HT trigger, and p_T cut on constituents biases trigger jet to “surface”

Au-Au near side jet spectra looks like pp



Trigger Jet:
R = 0.4
$p_{T,cut}$ = 2 GeV/c
p_T^{jet} > 20 GeV/c

Recoil Jet:
R = 0.4
$p_{T,cut}$ = 2 GeV/c

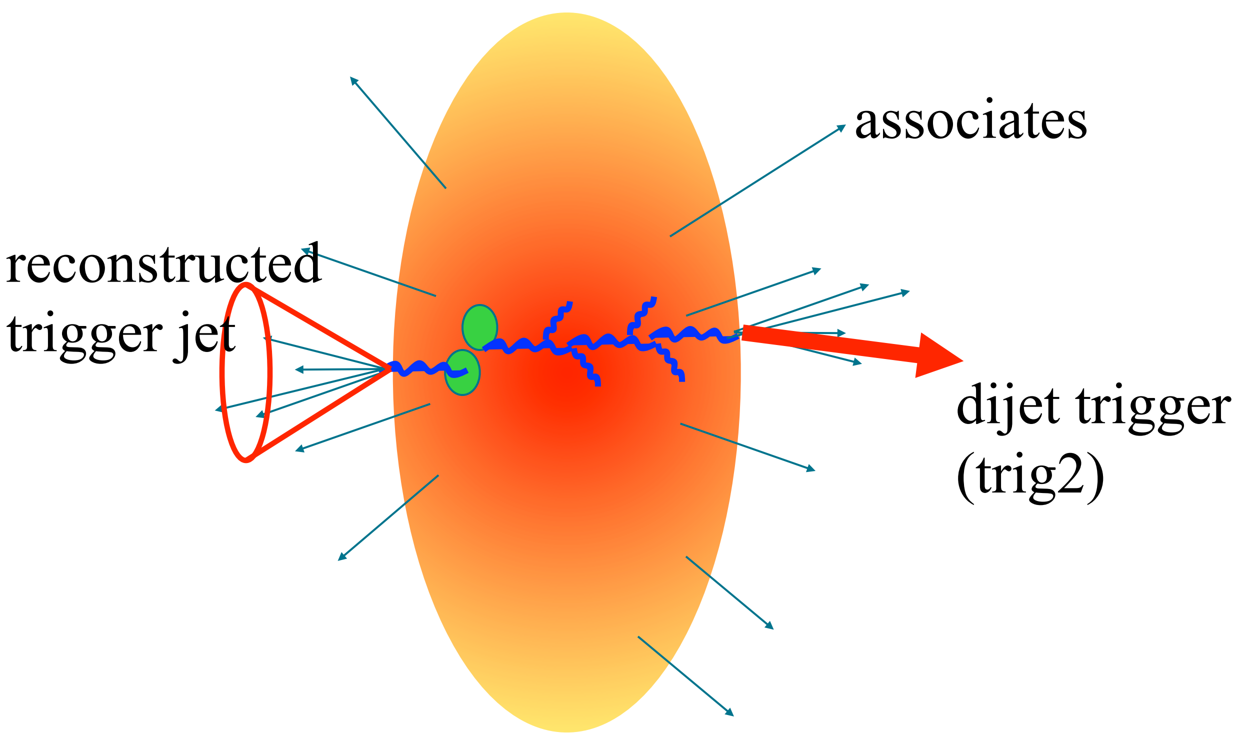
Recoil reconstruction rate suppressed

Softening and/or broadening outside of jet cone

Recoil jet lost when medium present

STAR, QM 2009

Jet-hadron meets 2+1 Correlations



Require a high-p_T hadron ~180^o away from reconstructed trigger jet

Jet-hadron and 2+1 Correlations

$10 < p_T^{jet} < 20$ GeV/c $|\varphi_{jet} - \varphi_{trig2}| > \pi - 0.2$

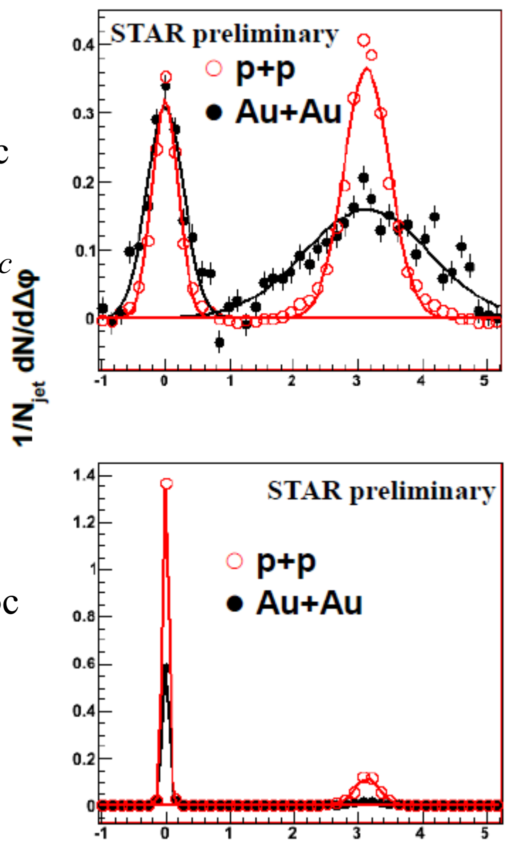
no trig2 requirement

Low p_T^{assoc}

$1.5 < p_T^{assoc} < 2$ GeV/c

High p_T^{assoc}

$6 < p_T^{assoc} < 8$ GeV/c



Jet-hadron and 2+1 Correlations

$10 < p_T^{jet} < 20$ GeV/c $|\varphi_{jet} - \varphi_{trig2}| > \pi - 0.2$

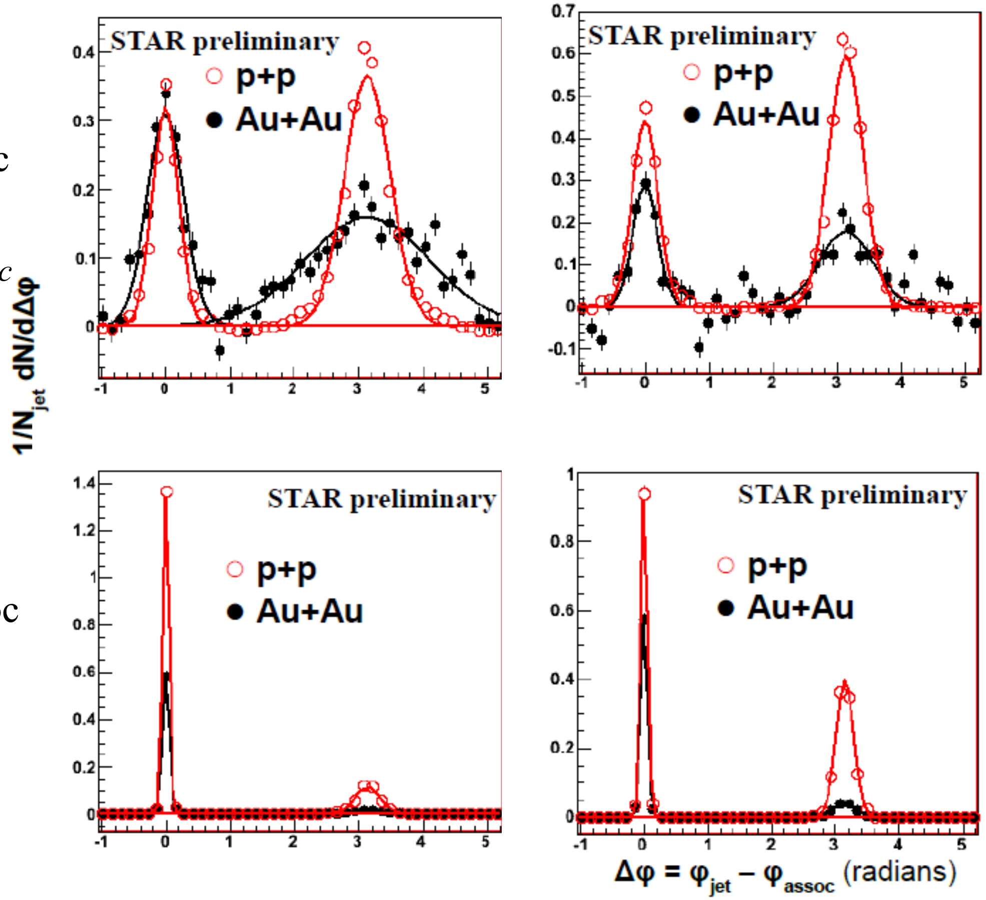
Low p_T^{assoc}

$1.5 < p_T^{assoc} < 2$ GeV/c

High p_T^{assoc}

$6 < p_T^{assoc} < 8$ GeV/c

no trig2 requirement $p_T^{trig2} > 2$ GeV/c



Jet-hadron and 2+1 Correlations

STAR, WWND 2011

$10 < p_T^{jet} < 20$ GeV/c $|\varphi_{jet} - \varphi_{trig2}| > \pi - 0.2$

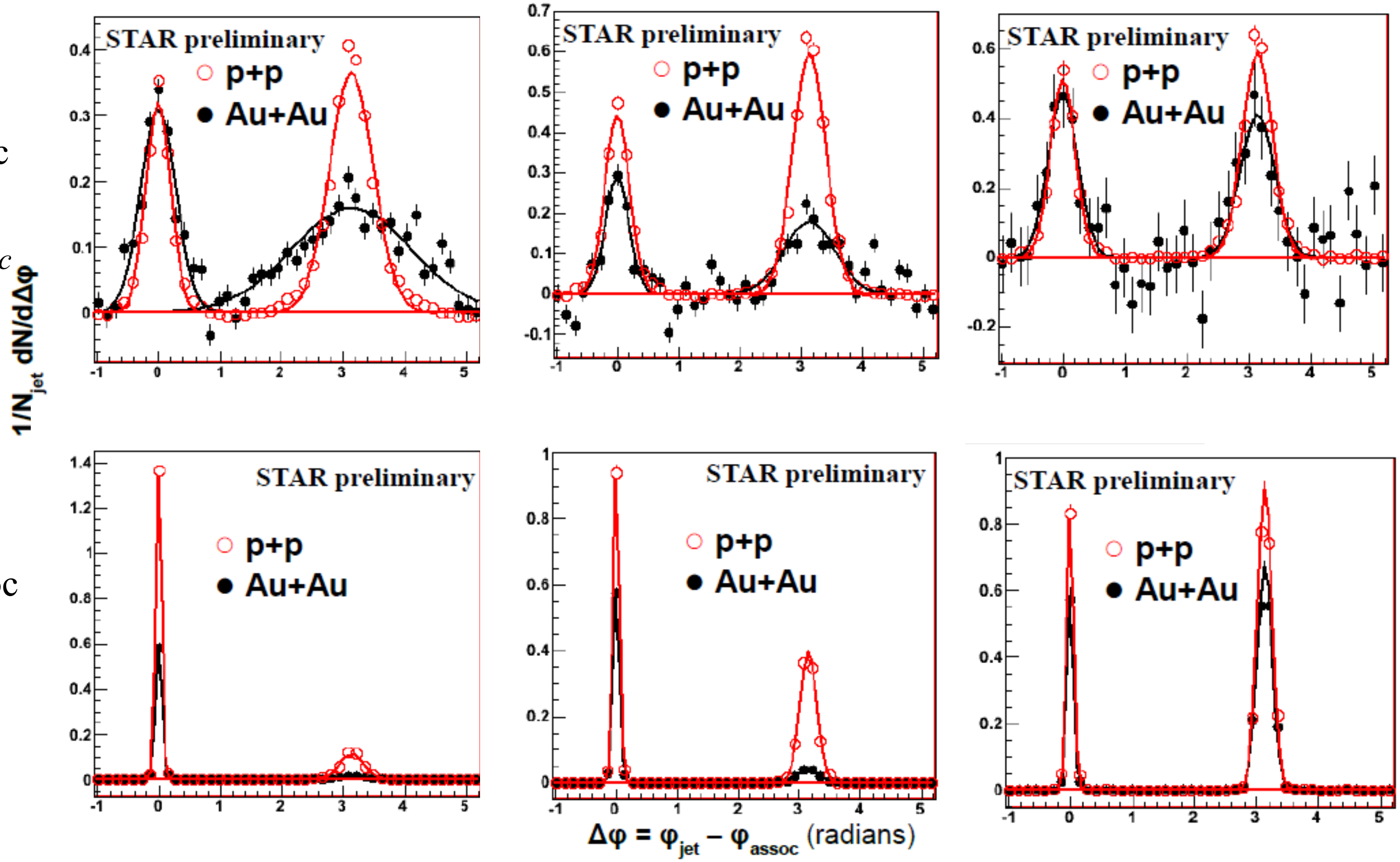
no trig2 requirement $p_T^{trig2} > 2$ GeV/c $p_T^{trig2} > 4$ GeV/c

Low p_T^{assoc}

$1.5 < p_T^{assoc} < 2$ GeV/c

High p_T^{assoc}

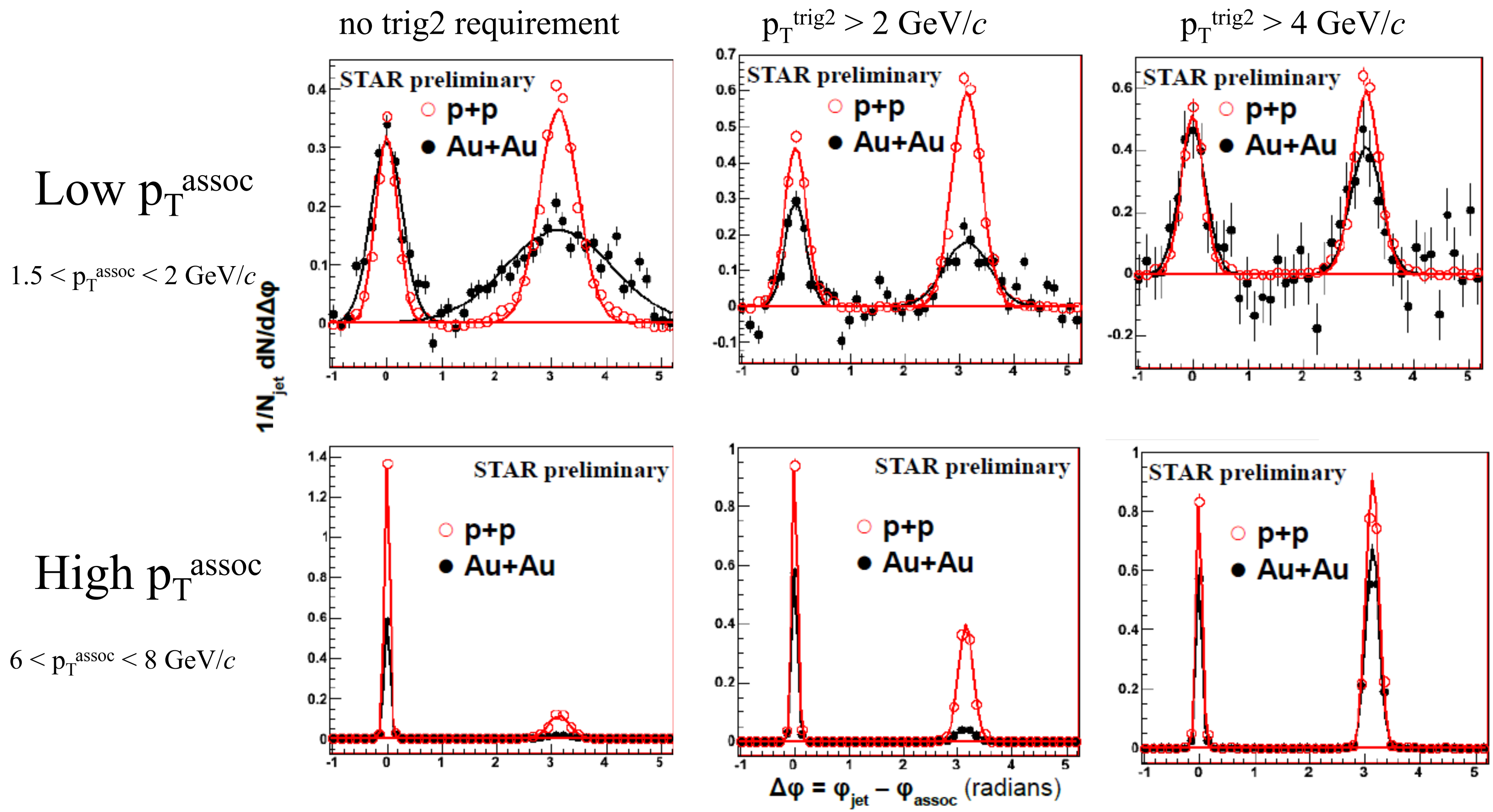
$6 < p_T^{assoc} < 8$ GeV/c



Jet-hadron and 2+1 Correlations

STAR, WWND 2011

$10 < p_T^{jet} < 20$ GeV/c $\quad |\varphi_{jet} - \varphi_{trig2}| > \pi - 0.2$



Select unmodified jets with $p_T^{hadron} > 4$ GeV/c requirement.

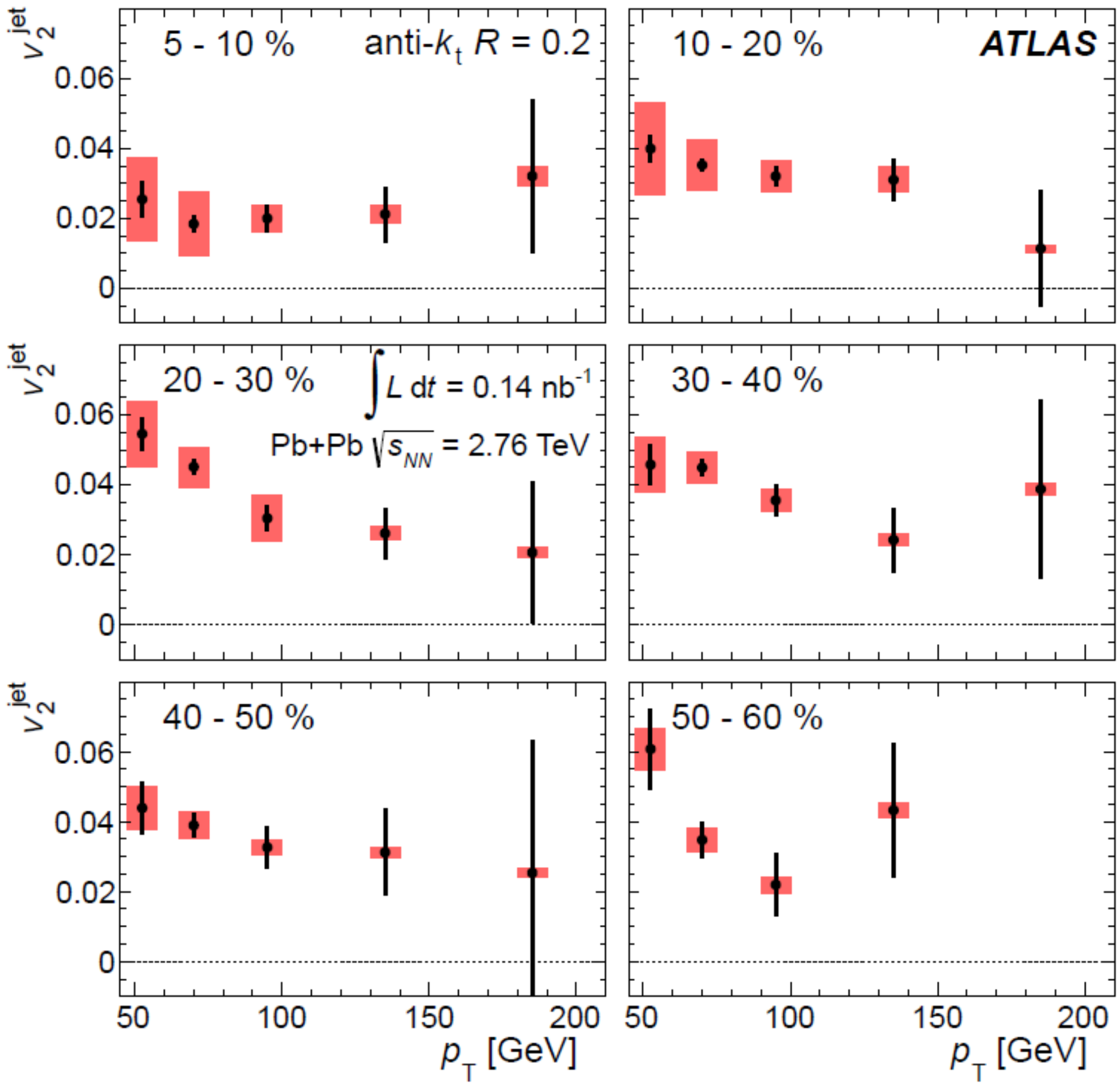
Summary

- Consistent picture emerging from RHIC studies
  - energy loss of high p_T goes to many low p_T particles at large angles
- Heavy flavour c and b potentially loosing similar amounts of energy as light quarks/gluons even though B R_{AA} > C R_{AA} = light quark/gluon R_{AA}
- d-Au data still confusing....
  - is there flow?
- is the Cronin effect the flow effect?
  - mass dependence
- Higher stats HF and more light-heavy nuclei collisions would be helpful
  - p-A and pp BES

- THE END

Jet v_2 at ATLAS

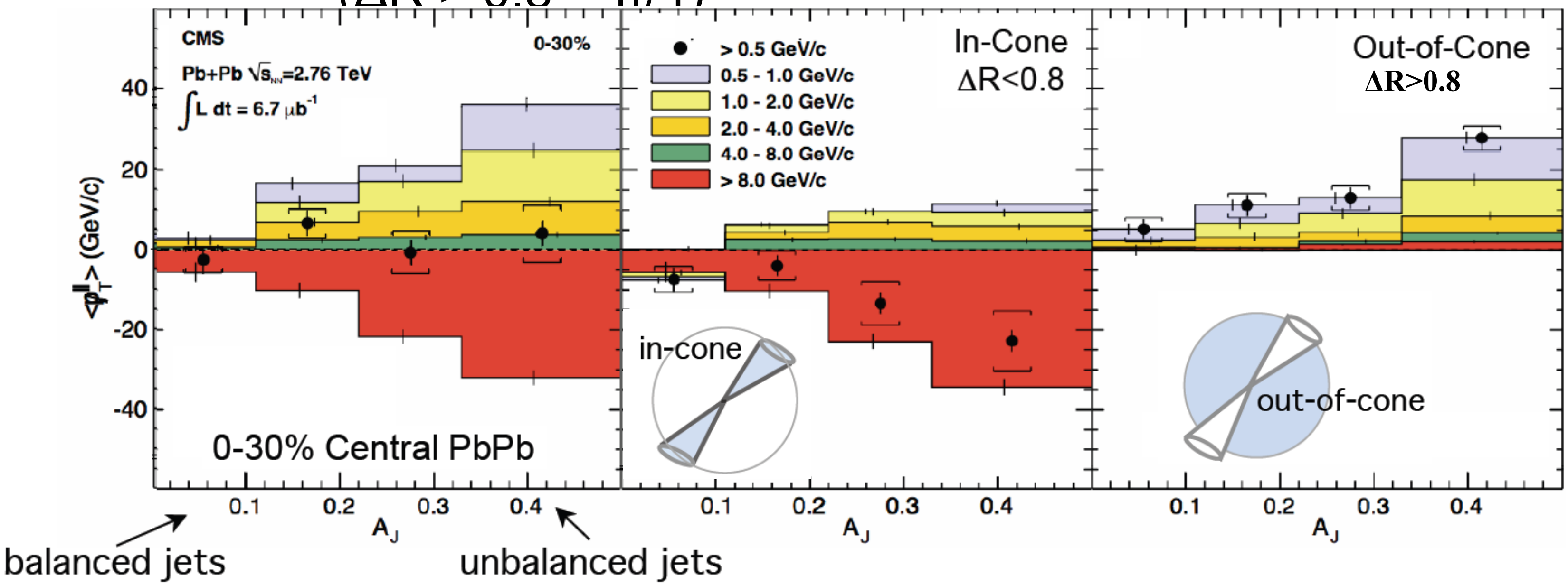
ATLAS, arXiv:1306.6469 [hep-ex]
Submitted to PRL



- Jet v_2 measured for
- $45 < p_T^{jet} < 210$ GeV/c, R = 0.2
- Also observed $v_2^{jet} > 0$
- Different kinematic range and biases than STAR measurement
  → different trend with p_T^{jet}

Jets at the LHC

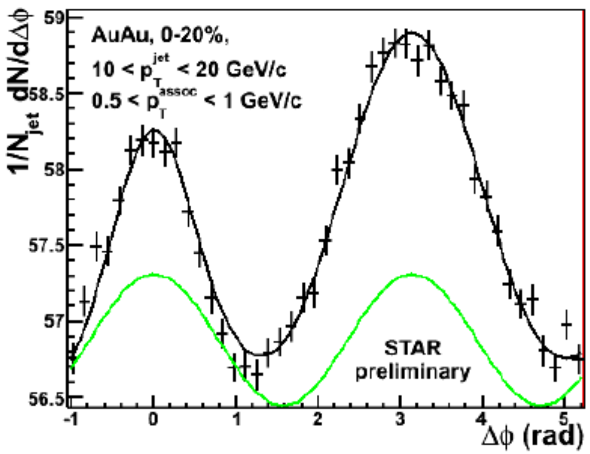
- CMS result → Energy is distributed to very wide angles ($\Delta R > 0.8 \sim \pi/4$)

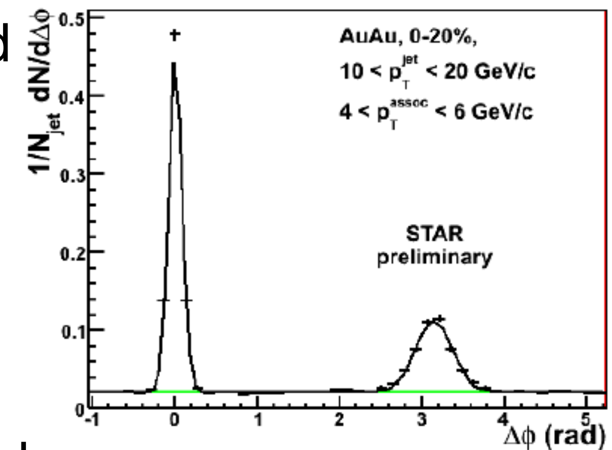


- Similar conclusions for CMS A_J and PHENIX γ-jet measurements
- Where does the "missing" energy go?

Jet-hadron Correlations

- Intentionally impose a bias towards unmodified trigger jets! (surface bias?)
  - E_T > 6 GeV in a single BEMC tower (Δφ x Δη = 0.05 x 0.05)
  - Anti-k_T (R = 0.4) using tracks/towers with p > 2 GeV/*c*
- HT trigger requirement and constituent p_T cut
  - Reduce effects of background fluctuations
  - Comparison to p+p is more straightforward
- Trigger (nearside) jet population is highly-biased
  - Used to assign uncertainties to shape of background (v_2 and v_3) and trigger jet energy scale
- Recoil (awayside) jet fragmentation is unbiased



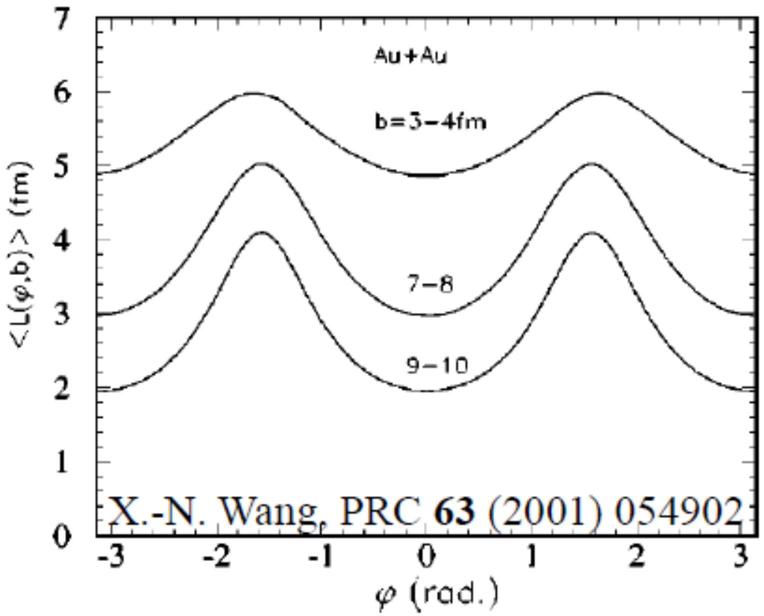


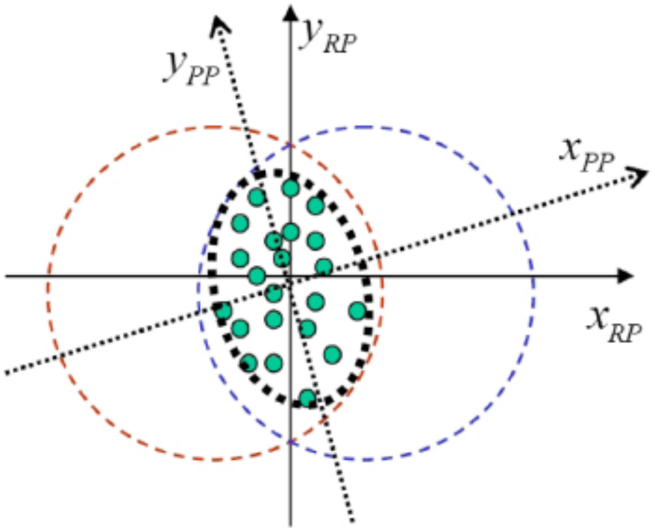
What is jet v_2?

In-medium pathlength depends on orientation to reaction plane

Pathlength-dependent jet quenching →

Energy/number of reconstructed jets may depend on orientation to reaction plane.





- "Jet v_2" → correlation between *reconstructed* jets and the reaction plane (or 2nd -order participant plane)
- "Jet v_2" ≠ "Jet flow"

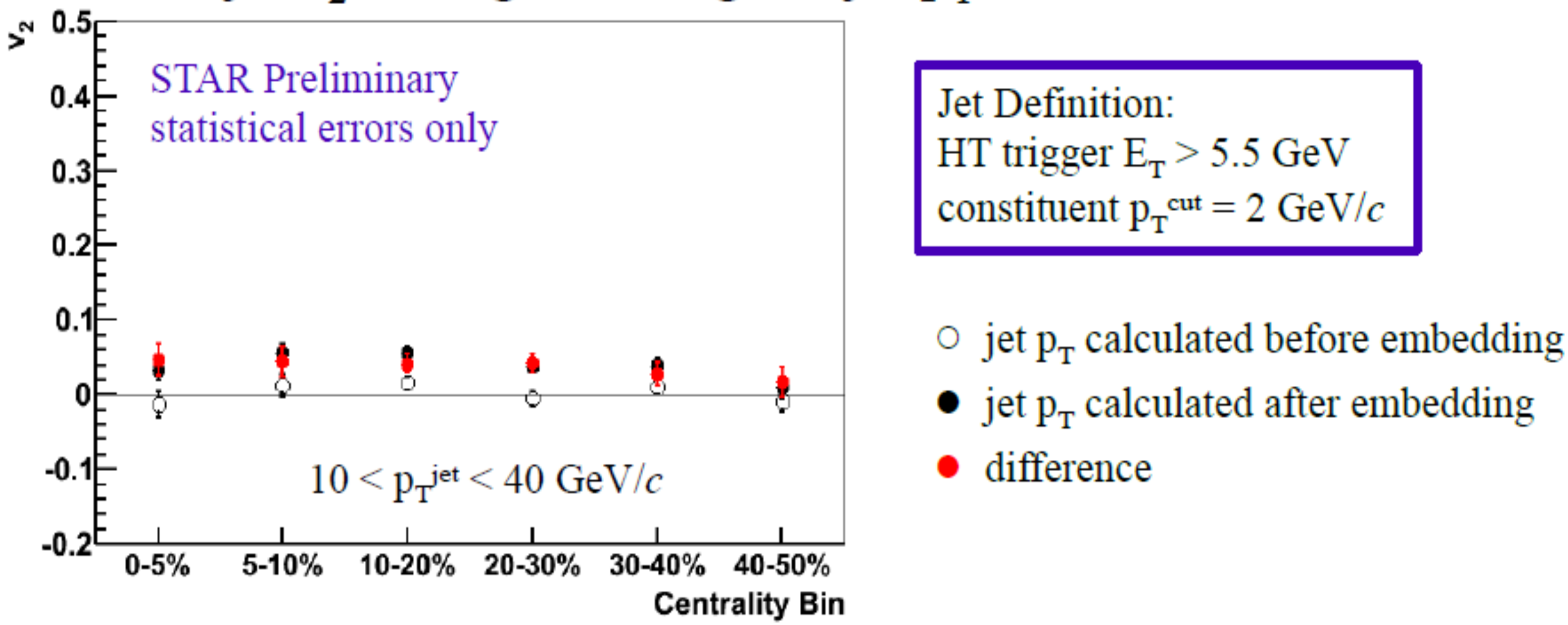
Artificial Sources of Anisotropy

- **Background Fluctuations and the Jet Energy Scale**
  Background particles (with $p_T > 2$ GeV/c) with significant v_2 are more likely to be clustered into the jet cone in-plane versus out-of-plane
  → more low-p_T jets reconstructed with a higher p_T
  → increased number of in-plane jets in a fixed reconstructed jet p_T range

- **Biased Event Plane**
  Jet fragments included in event plane calculation
  → event plane pulled towards jet

Background Fluctuations

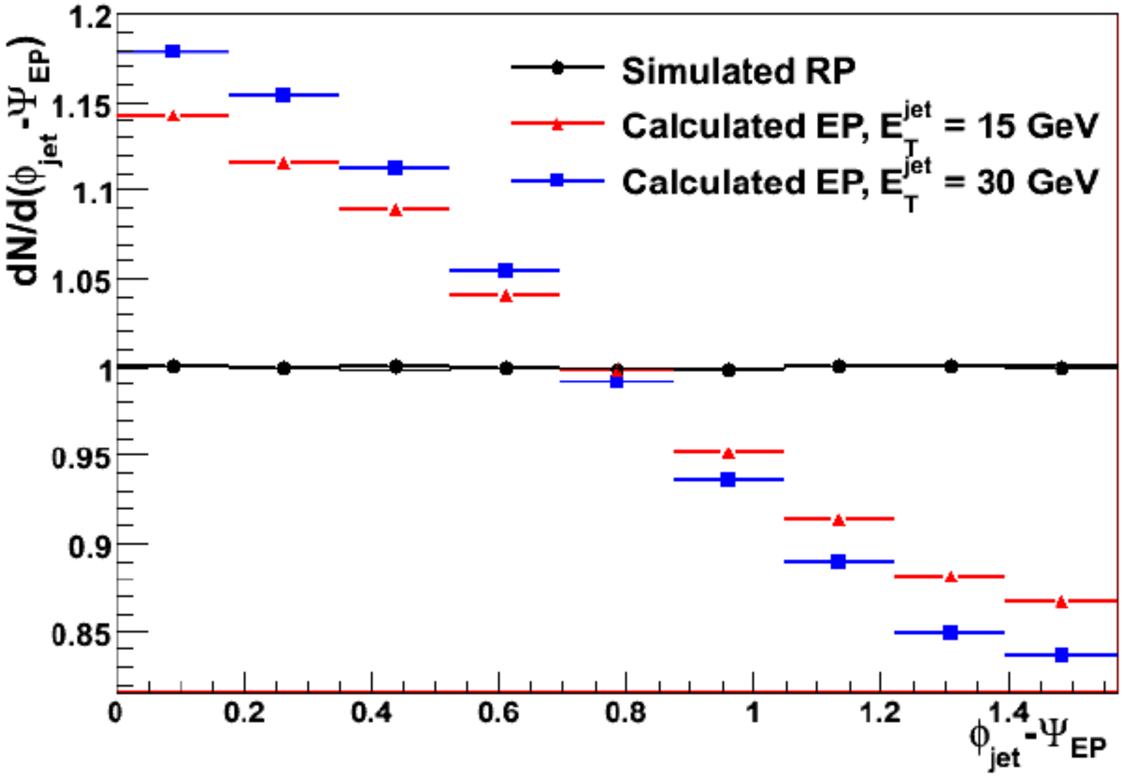
- Embed p+p HT jets isotropically into Au+Au minimum bias events
- Reconstruct p_T of p+p jet before and after embedding
- Correlate reconstructed jet axis with event plane of Au+Au event
- Calculate jet v_2 for a given range in jet p_T



Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c

- Artificial jet v_2 caused by background fluctuations is ~ 4%
- Subtract from measured jet v_2 values.

Jet - Event Plane bias

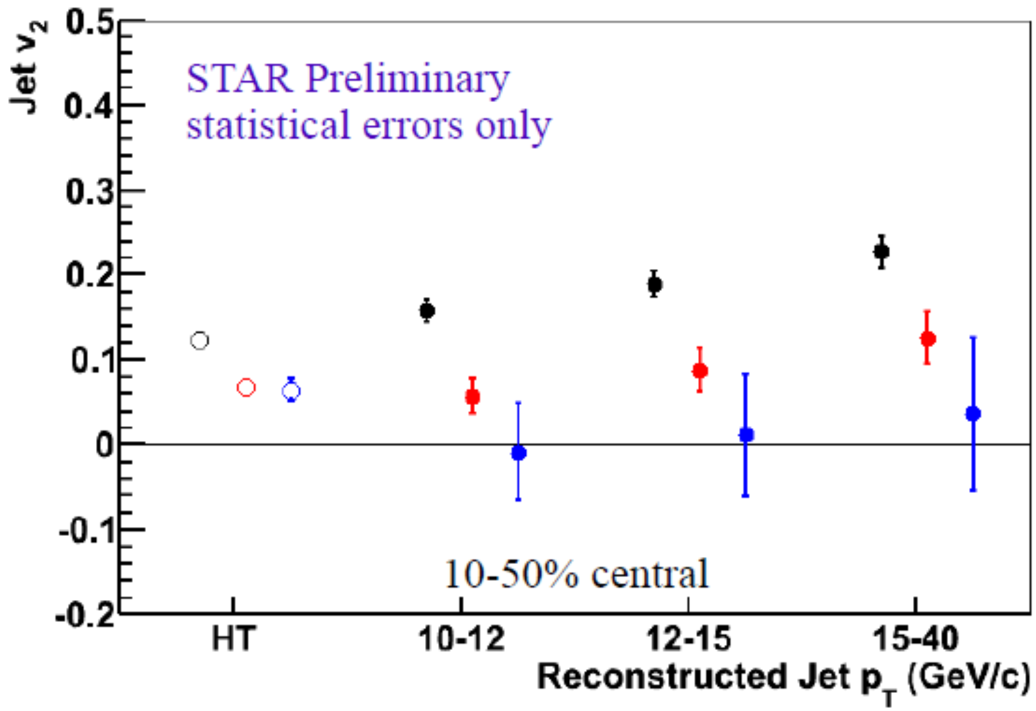


Simulation:
PYTHIA jets embedded
in thermal background

- Calculating the event plane at mid-rapidity leads to significant jet – event plane bias!

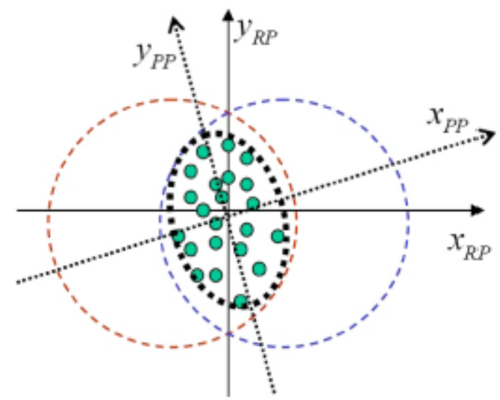
- Need to determine event plane at forward rapidities to measure jet v_2 at mid-rapidity...

Jet v_2 vs. Reconstructed Jet p_T



Jet Definition:
HT trigger E_T > 5.5 GeV
constituent p_T^{cut} = 2 GeV/c

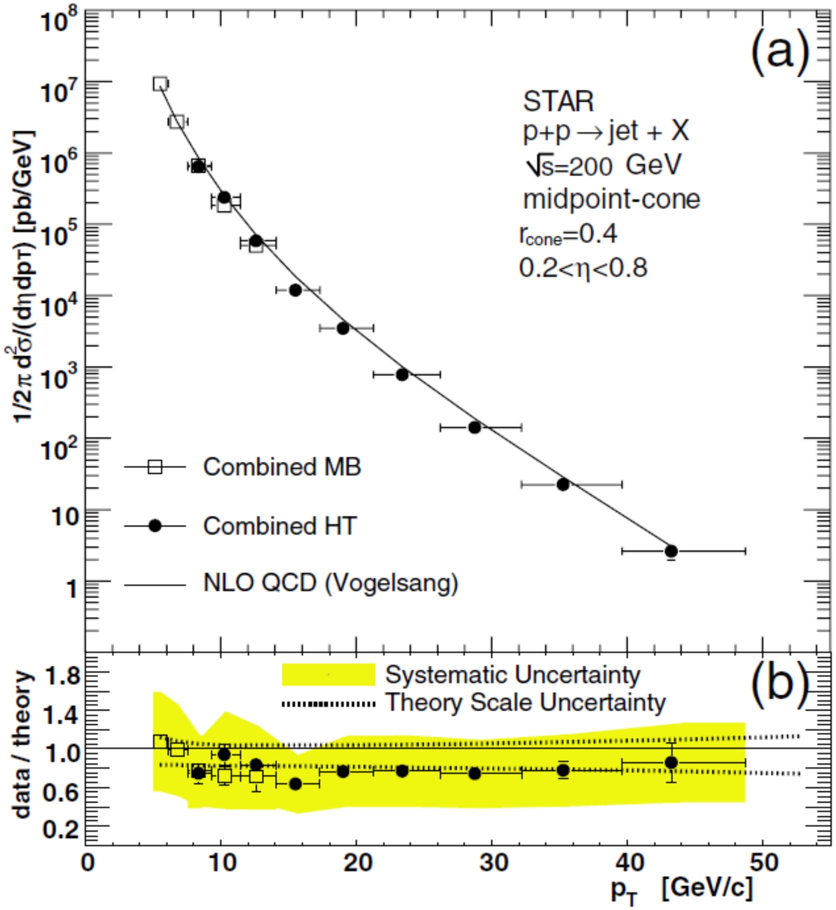
- Jet v_2\{TPC EP\}
- Jet v_2\{FTPC EP\}
- Jet v_2\{ZDC-SMD EP\}



- Jet v_2\{FTPC\} increases slightly with jet p_T
- Jet v_2\{FTPC\} > Jet v_2\{ZDC-SMD\}
  → In single-particle v_2 measurements, this difference is attributed to flow in participant plane vs. reaction plane, $v_2(PP) > v_2(RP)$
  → Jet energy loss sensitive to geometry in participant frame?

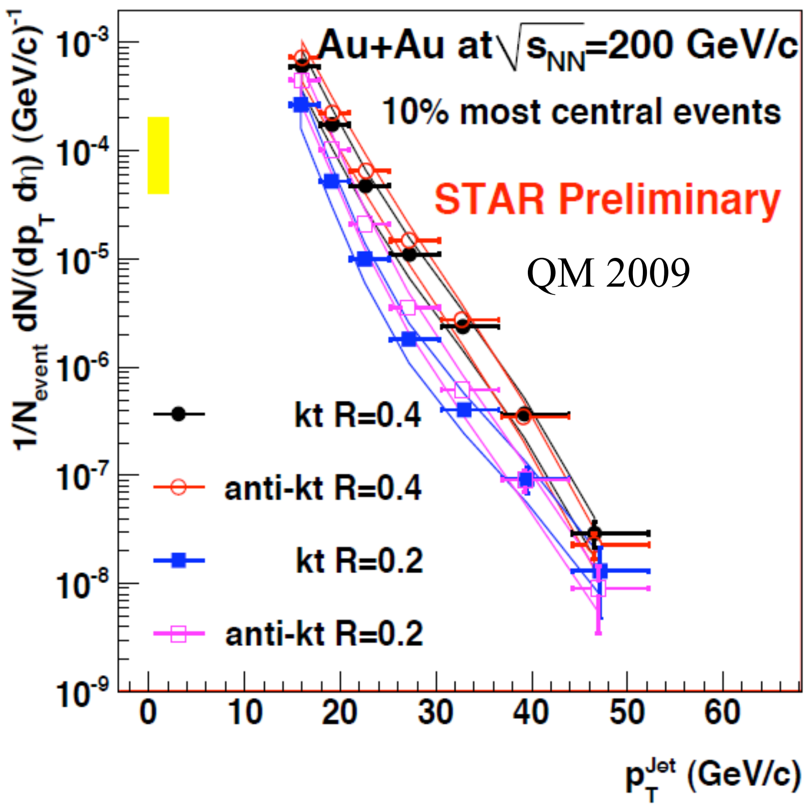
Jets in pp

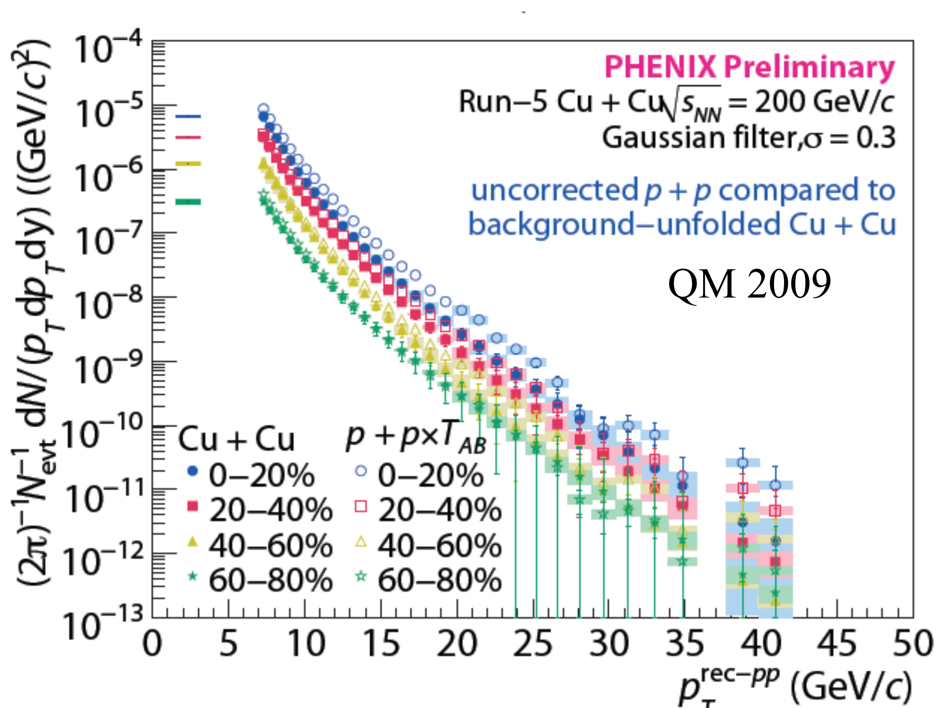
- Jets in pp are well-described by pQCD



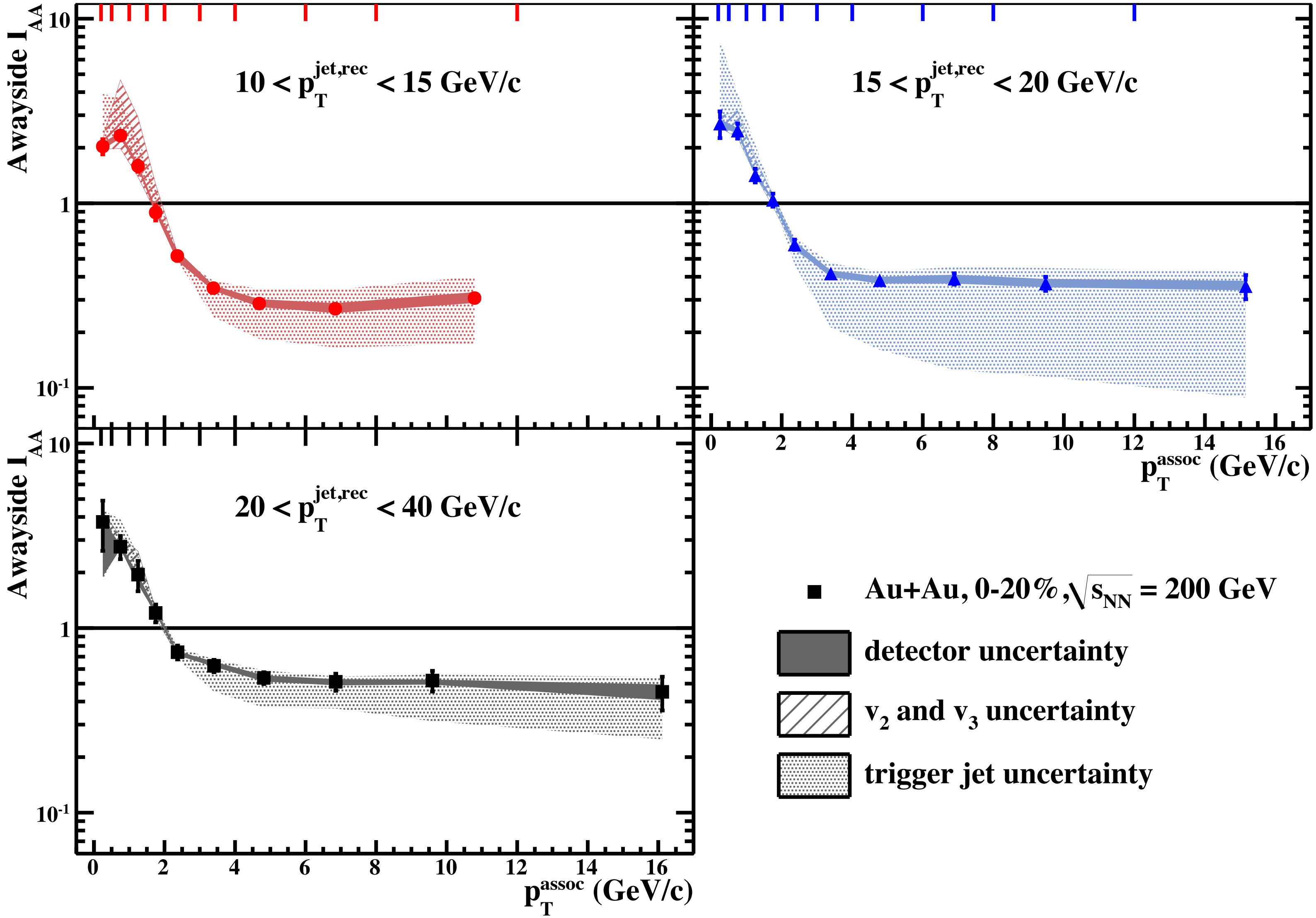
Jet Spectra at RHIC

- For the first time → Full jet reconstruction in a heavy ion environment
- Different methods of jet reconstruction, background subtraction, fake-jet rejection



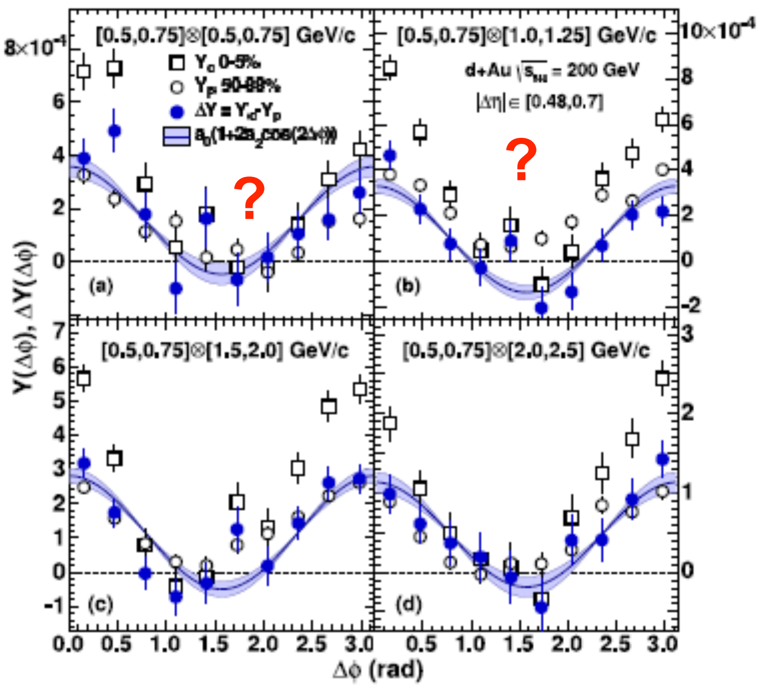


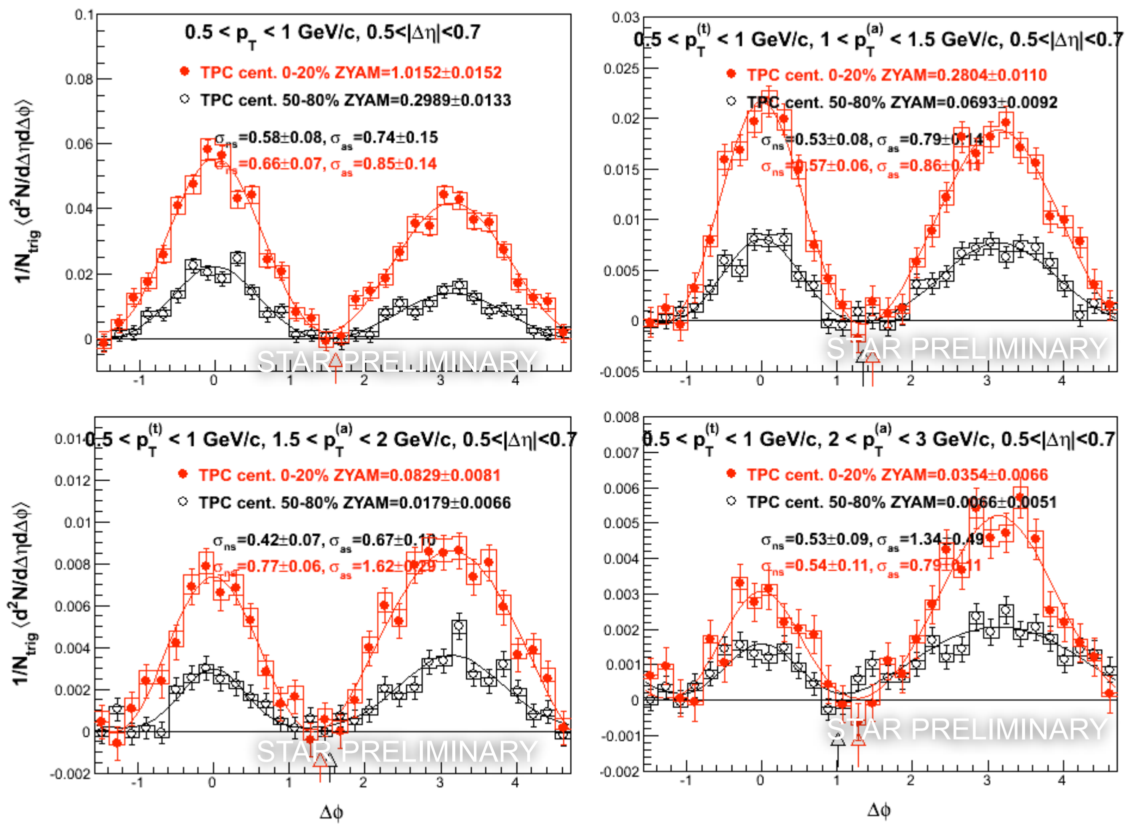
Awayside I_{AA}



Compare to PHENIX results

Note: not exact p_T matching





PHENIX not normalized by bin size?

Factor would be: 0.22x2x0.314=0.13

Then good consistency for the two high-p_T bins.

Not so for the two low-p_T bins.